

AD-A241 527



OCT 10 1991

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UCRL-21008 Vol. 8
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Evaluation of Military Field-Water Quality

**Volume 8. Performance of Mobile Water-Purification Unit (MWPU)
and Pretreatment Components of the 600-GPH Reverse Osmosis Water
Purification Unit (ROWPU), and Consideration of Reverse Osmosis (RO)
Bypass, Potable-Water Disinfection, and Water-Quality Analysis Techniques**

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May 1990

**Lawrence
Livermore
National
Laboratory**

**Supported by
U.S. Army Medical Research and Development Command
Fort Detrick, Frederick, MD 21701
Project Order 82PP2817
Project Officer: Dr. Stephen A. Schaub**

91-12861



81 10 8 100

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS -----		
2a. SECURITY CLASSIFICATION AUTHORITY -----			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE -----					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UCRL-21008 Vol. 8			5. MONITORING ORGANIZATION REPORT NUMBER(S) -----		
6a. NAME OF PERFORMING ORGANIZATION Lawrence Livermore National Laboratory		6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION U.S. Army Biomedical Research and Development Laboratory		
6c. ADDRESS (City, State, and ZIP Code) Environmental Sciences Division P.O. Box 5507, L-453 Livermore, CA 94550-0617			7b. ADDRESS (City, State, and ZIP Code) ATTN: SGRD-UBZ-C Fort Detrick (Building 568) Frederick, MD 21701-5010		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U.S. Army Medical Research and Development Command		8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Army Project Order 82PP2817		
8c. ADDRESS (City, State, and ZIP Code) Fort Detrick Frederick, MD 21701-5012			10. SOURCE OF FUNDING NUMBERS		
PROGRAM ELEMENT NO. 62787A		PROJECT NO. 3M1- 62787A875	TASK NO. AG	WORK UNIT ACCESSION NO. DA300881	
11. TITLE (Include Security Classification) Evaluation of Military Field-Water Quality. Volume 8. Performance of Mobile Water Purification Unit (MWPU) and Pretreatment Components of the 600-gph Reverse Osmosis Water Purification Unit (ROWPU) and Consideration of Reverse Osmosis (RO) Bypass, Portable-Water Disinfection, and Water-Quality Analysis Techniques					
12. PERSONAL AUTHOR(S) R.E. Selleck, Z. Ungun, G. Chester, V. Diyamandoglu, J.I. Daniels, and B. Marinas					
13a. TYPE OF REPORT FINAL		13b. TIME COVERED FROM 11-86 TO 5-90		14. DATE OF REPORT (Year, Month, Day) May 1990	
				15. PAGE COUNT 131	
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	Mobile Water Purification Unit; Reverse Osmosis Water Purification Unit; Pretreatment; Filtration; Disinfection; Water-Quality Analysis; Reverse Osmosis Bypass		
24	07				
06	11				
19. ABSTRACT (Continue on reverse if necessary and identify by block number) A comparison is made between the performances of the 600-gph Reverse Osmosis Water Purification Unit (ROWPU) operated in the bypass mode and the Mobile Water Purification Unit (MWPU, also referred to as an ERDLATOR). Generally, the performance of the MWPU is significantly better than the pretreatment units of the ROWPU in terms of removing both turbidity and pathogenic organisms. It is recommended that the practice of bypassing the reverse osmosis (RO) components of the ROWPU be avoided unless it can be demonstrated clearly that the cartridge filters will remove the cysts of infectious organisms effectively and reliably. If the ROWPU must be operated in the bypass mode, it is recommended that the dose of disinfectant used be made equal to that currently employed in the field for untreated raw water. The analytical methods used to determine total dissolved solids (TDS) and residual free chlorine with the new Water-Quality Monitor (WQM) are also reviewed briefly. The limitations of the methods used to calibrate the TDS and free-chlorine probes of the new WQM are discussed. (continued on next page)					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a. NAME OF RESPONSIBLE INDIVIDUAL Mary Frances Bostian			22b. TELEPHONE (Include Area Code) 301-663-7325		22c. OFFICE SYMBOL SGRD-RMI-S

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

This report is the eighth volume of a nine-volume study entitled Evaluation of Military Field-Water Quality. Titles of the other volumes are as follows: Vol. 1, Executive Summary; Vol. 2, Constituents of Military Concern from Natural and Anthropogenic Sources; Vol. 3, Opportunity Poisons; Vol. 4, Health Criteria and Recommendations for Standards; Vol. 5, Infectious Organisms of Military Concern Associated with Consumption: Assessment of Health Risks, and Recommendations for Establishing Related Standards; Vol. 6, Infectious Organisms of Military Concern Associated with Nonconsumptive Exposure: Assessment of Health Risks, and Recommendations for Establishing Related Standards; Vol. 7, Performance Evaluation of the 600-GPH Reverse Osmosis Water Purification Unit (ROWPU): Reverse Osmosis (RO) Components; and Vol. 9, Data for Assessing Health Risks in Potential Theaters of Operation for U.S. Military Forces.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

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Supported by
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Project Order 82PP2817

Project Officer: S. A. Schaub

Principal Investigators at Lawrence Livermore National Laboratory:
L. R. Anspaugh, J. I. Daniels, and D. W. Layton

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of the Army position unless so designated by other authorized documents.

*** Sanitary Engineering and Environmental Health Research Laboratory [Building 112],**
University of California, Richmond Field Station, Richmond, CA 94804.

FOREWORD

This report is the eighth volume of a nine-volume study entitled Evaluation of Military Field-Water Quality. Titles of the other volumes are as follows: Vol. 1, Executive Summary; Vol. 2, Constituents of Military Concern from Natural and Anthropogenic Sources; Vol. 3, Opportunity Poisons; Vol. 4, Health Criteria and Recommendations for Standards; Vol. 5, Infectious Organisms of Military Concern Associated with Consumption: Assessment of Health Risks, and Recommendations for Establishing Related Standards; Vol. 6, Infectious Organisms of Military Concern Associated with Nonconsumptive Exposure: Assessment of Health Risks, and Recommendations for Establishing Related Standards; Vol. 7, Performance Evaluation of the 600-GPH Reverse Osmosis Water Purification Unit (ROWPU): Reverse Osmosis (RO) Components; and Vol. 9, Data for Assessing Health Risks in Potential Theaters of Operation for U.S. Military Forces.

The nine volumes of this study contain a comprehensive assessment of the chemical, radiological, and biological constituents of field-water supplies that could pose health risks to military personnel as well as a detailed evaluation of the field-water-treatment capability of the U.S. Armed Forces. The scientific expertise for performing the analyses in this study came from the University of California Lawrence Livermore National Laboratory (LLNL) in Livermore, CA; the University of California campuses located in Berkeley (UCB) and Davis (UCD), CA; the University of Illinois campus in Champaign-Urbana, IL; and the consulting firms of IWG Corporation in San Diego, CA, and V.J. Ciccone & Associates (VJCA), Inc., in Woodbridge, VA. Additionally a Department of Defense (DoD) Multiservice Steering Group (MSG), consisting of both military and civilian representatives from the Armed Forces of the United States (Army, Navy, Air Force, and Marines), as well as representatives from the U.S. Department of Defense, and the U.S. Environmental Protection Agency provided guidance, and critical reviews to the researchers. The reports addressing chemical, radiological, and biological constituents of field-water supplies were also reviewed by scientists at Oak Ridge National Laboratory in Oak Ridge, TN, at the request of the U.S. Army. Furthermore, personnel at several research laboratories, military installations, and agencies of the U.S. Army and the other Armed Forces provided technical assistance and information to the research on topics related to field water and the U.S. military community.

ACKNOWLEDGMENTS

The authors extend their appreciation to the scientists and staff of the Environmental Sciences Division at the Lawrence Livermore National Laboratory (LLNL), as well as to Dr. Stephen A. Schaub and his colleagues at the U.S. Army Biomedical Research and Development Laboratory (USABRDL), for their cooperation and assistance. A special thank you is extended to the scientists and staff of the Sanitary Engineering and Environmental Health Research Laboratory at the University of California, Richmond Field Station, and at the University of California, Berkeley, for their efforts in preparing this document. The authors also express their gratitude to those individuals and organizations in the reverse osmosis industry who provided information about reverse osmosis technology that was intrinsic to our research, and to Dr. G.C. White for his review of the material related to disinfection procedures and analytical methods for the assessment of field-water quality.

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PREFACE

This work is Volume 8 of the series, Evaluation of Military Field-Water Quality, and it is concerned primarily with the performance of the mobile water-purification unit (MWPU) and the pretreatment components of the 600-GPH reverse osmosis water purification unit (ROWPU) available in 1986. A performance evaluation of the reverse osmosis (RO) components of the ROWPU appears in Volume 7, the companion volume to Volume 8. Also considered in this volume are (1) the efficacy of the operation of the ROWPU in a mode that bypasses the RO components, (2) the potable-water disinfection processes available to the U.S. Armed Forces, and (3) the water-quality analysis techniques applicable to field water. Together, Volumes 7 and 8 represent a complete assessment of the treatment, disinfection, and water quality analysis procedures now used by U.S. military forces.

ABSTRACT

A comparison is made between the performances of the 600-gph Reverse Osmosis Water Purification Unit (ROWPU) operated in the bypass mode and the Mobile Water Purification Unit (MWPU, frequently referred to as an ERDLATOR because the equipment was developed at the Engineer Research and Development Laboratory at Fort Belvoir, VA). Generally, the performance of the MWPU is significantly better than the pretreatment units of the ROWPU in terms of removing both turbidity and pathogenic organisms. It is recommended that the practice of bypassing the reverse osmosis (RO) components of the ROWPU be avoided unless it can be demonstrated clearly that the cartridge filters will remove the cysts of infectious organisms effectively and reliably. If the ROWPU must be operated in the bypass mode, it is recommended that the dose of disinfectant used be made equal to that currently employed in the field for untreated raw water.

The analytical methods used to determine total dissolved solids (TDS) and residual free chlorine with the new Water-Quality Monitor (WQM) are also reviewed briefly. The limitations of the methods used to calibrate the TDS and free-chlorine probes of the new WQM are discussed.

INTRODUCTION

The U.S. Army is considering the use of the 600-gph Reverse Osmosis Water Purification Unit (ROWPU) in an alternate configuration, here called the "bypass mode". Only the multimedia and cartridge filters would be utilized, followed by chemical disinfection. The advantage of this is that the loss of between 1/2 and 2/3 of the filtered water as RO reject water would be avoided. A second benefit of this arrangement would be cutting the power requirements in half, because roughly 50% of the power supplied to the ROWPU is used in the reverse osmosis (RO) process.¹

The treatment system in the bypass mode would include the following components: (1) a garnet-sand-anthracite deep-bed multimedia pressure filter, (2) a 5- μ m (nominal rating) cartridge filtration unit, and (3) chlorination with a chlorine dose equivalent to 5 to 10 mg/L of free-chlorine residual, depending on the pH, temperature, and other feed-water-quality parameters. Three criteria were suggested by the U.S. Army planners to be considered in the treatment of raw waters in the bypass mode.² These criteria were as follows:

- The water must be free of "acute toxicity from industrial, agricultural, domestic, or natural resource contributions."
- The water must satisfy potability requirements regarding NBC (nuclear, biological, and chemical) warfare agents.
- The water must meet palatability requirements.

Modifications to the treatment train have been considered by the U.S. Army planners. Two of the alternatives under consideration are² (1) reducing the pore size of the cartridge filters from a nominal rating (defined by a military test) of 5 μm to an absolute rating (the diameter of the largest spherical particle passing through a filter) of 3 μm , and (2) using alternative disinfectants that might have viricidal and cysticidal properties superior to those of chlorine. A major concern expressed by the U.S. Army planners was the health risk inherent in the failure to remove pathogenic viruses and cysts when bypassing the RO section of the 600-gph ROWPU.

The objectives of this report are to review and summarize the state of knowledge concerning primarily the removal of microorganisms achieved with multimedia deep-bed filters operated in the direct-filtration mode equivalent to that proposed for the 600-gph ROWPU bypass, and to compare the results with those that can be expected for the current 3000-gph Mobile Water Purification Unit (MWPU). In this way the U.S. Army can judge better the risks associated with bypassing the RO section of the ROWPU and can compare them with the risks associated with the use of the MWPU.

CONCEPTS OF DEEP-BED FILTRATION

The pretreatment portion of the current 600-gph ROWPU contains a deep-bed multimedia filter. Deep-bed filtration or depth filtration may be defined as a process in which a fluid suspension is passed through a filter composed of granular or fibrous materials. The suspended solids are deposited on the surfaces of the grains or fibers along the entire filter depth as the water flows through the filter media.³

A second general type of filtration is surface filtration. In this case the solids are strained from the water at the surface of the filter medium. Straining occurs if the sizes of the particles in suspension are greater than about 0.2 times the filter grain size.⁴ Precoat filters of the type used in the MWPU are commonly considered to be surface filters. A filter may act both as a surface and deep-bed filter, depending primarily on the physical and chemical characteristics of the suspension and the filter media, as well as the rate of filtration.³

In water treatment, the process of destroying the stabilizing forces that keep the colloidal particles apart is referred to as "chemical coagulation." According to Weber,³ coagulation is the overall process of colloidal particle aggregation, including both destabilization and transport, whereas flocculation is just the particle transport that occurs after destabilization. Following the mixing of the coagulating chemicals with the colloidal suspension, several complex reactions take place. These reactions are fast, taking place in less than one second. At this point in the process, the colloids are destabilized, and any particle formed is very small.

The rate of agglomeration at which the destabilized particles form visible flocs is dependent on the number of opportunities for particle-particle contact. When the water containing the destabilized particles is passed through a granular deep-bed filter column, flocculation takes place at a greatly accelerated rate because of the large number of opportunities for contact between the destabilized particles afforded by the passage of the water in the tortuous flow pathways. The floc particles then become attached to or adsorbed by the surface of the filter grains. As the filtration run progresses, the pores in the upper section of the filter medium gradually fill with floc, and the particles move down into the filter to find an available surface for attachment. Finally, the pressure drop across the filter bed increases to an undesirable level or breakthrough occurs. Consequently, filter backwashing is required.

The terms direct and conventional water filtration apply to the mode of filter operation. In direct filtration, all solids (those occurring naturally in the raw water and those added during the treatment) must be removed and stored in the filter bed.⁵ On the other hand, in conventional water filtration some of the solids are removed in a sedimentation basin located upstream from the filter. According to the Coagulation-Filtration Committee of the American Water Works Association (AWWA), direct filtration refers to a treatment system in which filtration is not preceded by sedimentation, and consequently those systems that do not use any chemicals for pretreatment are not considered direct-filtration systems.⁶ The main steps in the direct-filtration process are the following: (1) the addition of the destabilizing chemicals, (2) complete or partial flocculation with no settling, and (3) filtration. The flocculation step may be eliminated depending on the raw-water quality.⁵ The flow schemes shown in Fig. 1 illustrate the differences between conventional and direct filtration, as well as the differences between the various versions of direct filtration.

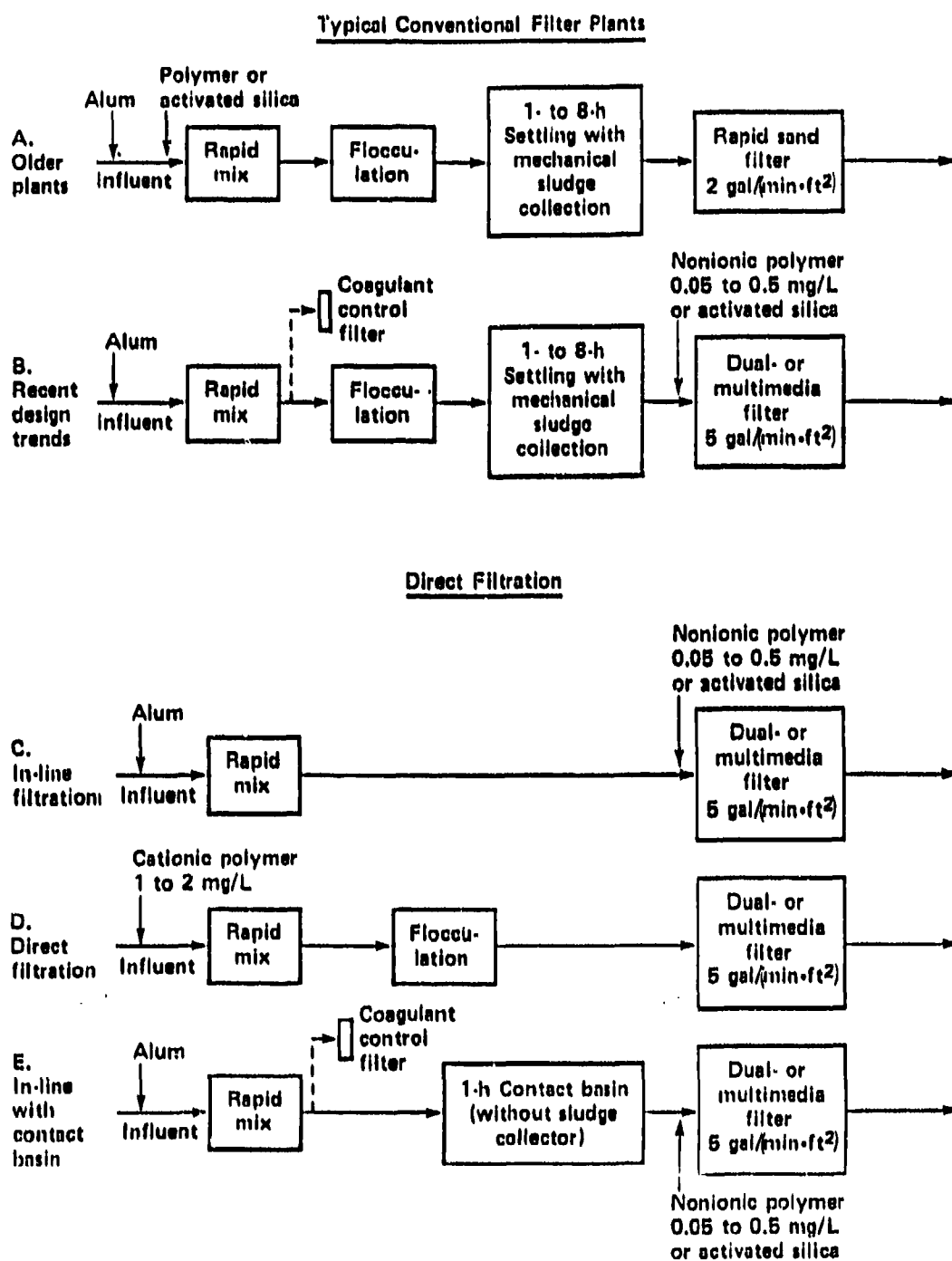


Figure 1. Classification of modes of filter operation. Adapted from Culp.⁶

THEORY

According to O'Melia and Stumm,⁷ filtration is similar to coagulation in the sense that removal within a deep-bed filter column involves at least two separate steps: (1) particle transport and (2) particle attachment. Particle transport, a physical-hydraulic process, is principally affected by parameters governing the mass transfer. On the other hand, particle attachment, basically a chemical process, is influenced by both chemical and physical parameters.

Particle Transport

O'Melia and Stumm⁷ and Yao *et al.*⁸ studied deep-bed filtration from a microscopic point of view. According to those authors, the suspended solids are removed by the following two-step process: (1) the mass transport of the suspended solids to the immediate vicinity of the solid-liquid interface of the filter media, and (2) the attachment of particles to the media. A simplified mass-transport model was postulated in which a single grain of the filter media (henceforth called the collector) is separated from the surrounding grains and fixed in space. The water flows in the direction of the gravitational force in a laminar regime. Stokes' equations were used to compute laminar-flow velocities around the spherical collector. Coagulation theory was then used to compute the number of contacts that would occur per unit time between a collector of diameter d_g and a uniform suspension (i.e., all particles having the same size) of spherical particles of diameter d_p , as shown in Fig. 2.

The transport mechanisms by which suspended particles are collected are interception, sedimentation, and diffusion. According to Fig. 2, a suspended particle will touch or intercept the collector when the particle is contained in a flowing-fluid streamline that passes within a distance of $d_p/2$ of the collector (point A in Fig. 2). Inertial and gravitational forces may also cause the particle to deviate from a streamline (i.e., sedimentation) and collide with the collector (path B in Fig. 2). The third mechanism, Brownian motion or diffusion, may also cause the particles to cut across the streamlines and collide with the collector (path C in Fig. 2). In water suspension the inertial effect on particle collection is very small and has been ignored by O'Melia and Stumm⁷ and Yao *et al.*⁸ in their works. Other possible forces such as electrostatic or van der Waals forces have also been ignored.

A materials balance may be written about a differential volume to obtain the temporal and spatial variation in n , the number of suspended particles per unit volume of water:⁸

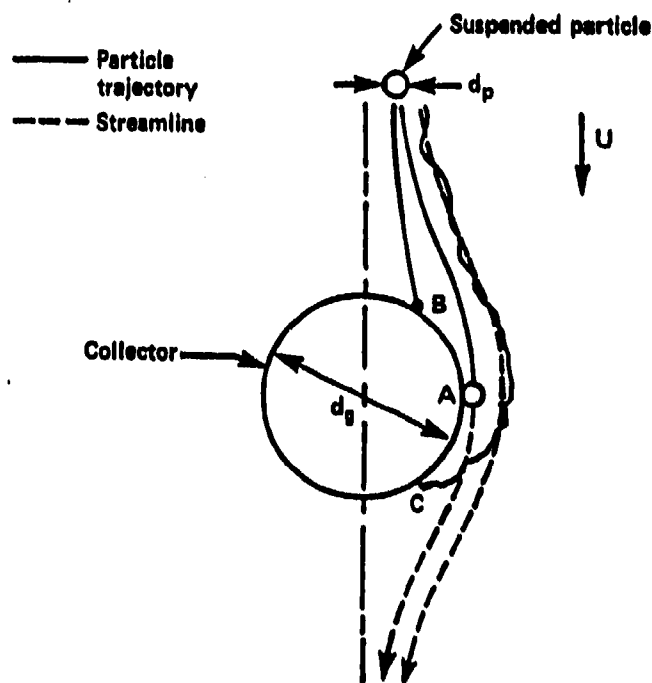


Figure 2. The single-collector theory according to Yao et al. A = interception, B = sedimentation, C = diffusion, U = velocity (well removed from collector) at which particles approach the collector. Adapted from Yao et al.⁸

$$\frac{\partial n}{\partial t} + \bar{v} \cdot \bar{\nabla} n = D_p \nabla^2 n + \left(1 - \frac{\rho}{\rho_p}\right) \frac{m \cdot g}{3\pi \cdot \mu \cdot d_p} \cdot \frac{\partial n}{\partial z}, \quad (1)$$

In which

- D_p = the particle Brownian-motion diffusion coefficient ($L^2 T^{-1}$)
- \bar{v} = streamline-flow velocity (a vector) ($L T^{-1}$)
- g = gravitational acceleration ($L T^{-2}$)
- m = mass of a suspended particle (M)
- ρ and ρ_p = densities of the water and the suspended particles respectively ($M L^{-3}$)
- μ = water dynamic viscosity ($M L^{-1} T^{-1}$)
- z = coordinate in the direction of gravity (L)
- t = time (T)
- d_p = diameter of spherical particle (L)
- $\bar{\nabla} n$ = gradient in the number of particles, general (vector notation)
- L, M, T = units of length, mass, time

The first term on the left-hand side of the equation $\left(\frac{\partial n}{\partial t}\right)$ gives the temporal variation of n at any point (x,y,z) . The second term, $(\bar{v} \cdot \bar{\nabla} n)$ describes the effect of advection on the concentration at that point. The first term $(D_p \nabla^2 n)$ on the right-hand side of the equation describes the effect of diffusion, and the second term the effect of gravitational settling if the particles settle in accord with Stokes' law. The effect of interception on particle collection is included in the boundary conditions used to integrate Eq. 1.

Equation 1 has been solved analytically by considering the following assumptions: (1) $\frac{\partial n}{\partial t} = 0$ (steady state); (2) all the suspended particles that touch the collector disappear instantaneously from the system without increasing the size of the collector (the collector is always clean); and (3) only one removal mechanism is predominant at a specific suspended particle size d_p . The results obtained were expressed in terms of a single-collector efficiency η , which is defined as

$$\eta = r_g / U n A_g, \quad (2)$$

in which

r_g = rate at which the suspended particles touch or strike the collector (number of particles $\cdot T^{-1}$);

U = velocity at which the particles approach the collector, well removed from the collector ($L \cdot T^{-1}$);

n = particle concentration upstream from the collector (number of particles $\cdot L^{-3}$); and

A_g = cross-sectional area of the collector $= \pi d_g^2 / 4$ (L^2).

The analytical solutions based on the assumptions described previously are:

$$\text{Interception only: } \eta_I = 3 (d_p / d_g)^2 / 2 \quad (3)$$

$$\text{Sedimentation only: } \eta_G = \frac{(\rho_p - \rho) g d_p^2}{18 \mu U} \quad (4)$$

$$\text{Diffusion only: } \eta_D = 4(\eta_p / U d_g)^{2/3}, \quad (5)$$

in which

$$D_p = kT_a / 3\pi\mu d_p \quad (6)$$

and

$$k = \text{Boltzmann constant} = 1.39 \times 10^{-16} \text{ erg/K}$$

$$T_a = \text{absolute temperature (K)}.$$

Equations 3, 4, and 5 are plotted in Fig. 3 for the special case of $U = 2 \text{ gal}/(\text{min} \cdot \text{ft}^2)$, $d_g = 0.5 \text{ mm}$, $\rho_p = 1.05 \text{ g/cm}^3$, at 25°C . A numerical solution of Eq. 1 (curved line shown in Fig. 3) demonstrates that the overall collector efficiency can be obtained without significant error simply by adding Eqs. 3, 4, and 5;

$$\eta = \eta_I + \eta_G + \eta_D \quad (7)$$

The results shown in Fig. 3 demonstrate that

- There exists a size of the suspended particles for which the removal efficiency is a minimum. For conditions typical of conventional water-filtration practice, this size is about $1 \mu\text{m}$ and particles of greater or lesser size than $1 \mu\text{m}$ are removed more effectively.
- For example, for particles smaller than $1 \mu\text{m}$, the collector efficiency increases with decreasing particle size, and particle removal is accomplished by diffusion.
- For particles greater than $1 \mu\text{m}$, the collector efficiency increases rapidly with increasing particle size, and removal is accomplished by interception and/or sedimentation.

Conceptually, a single isolated collector is very different from a packed bed of collectors. With the collectors in contact with each other, the flow streamlines are not as pictured in Fig. 2. Even so, the single-collector theory has been applied directly to deep-bed filtration with reasonably good results, as will be demonstrated subsequently.

The number of single collectors contained in a differential volume element (i.e., having dimensions so tiny that particle behavior can be described using differential equations) of bed of thickness δz (see Fig. 4) is:

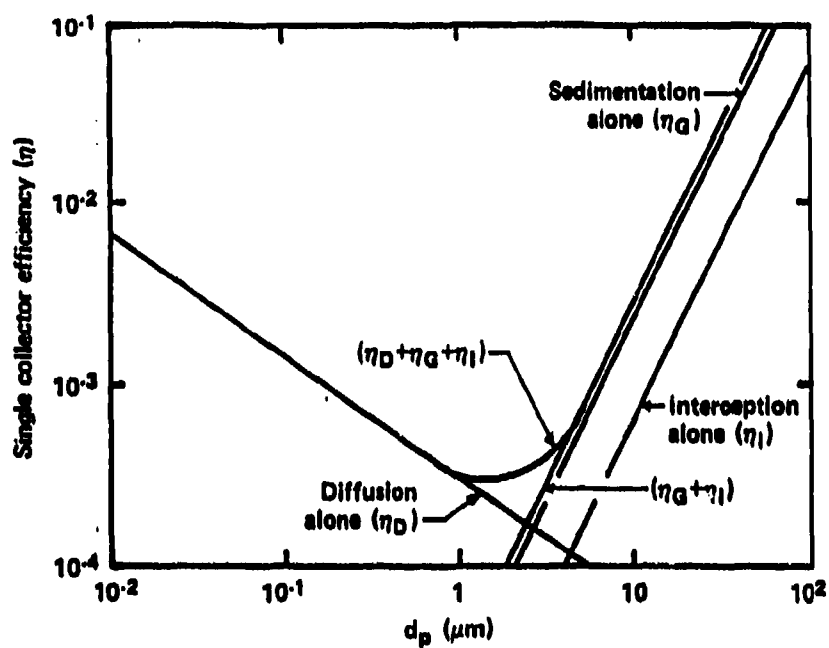


Figure 3. Comparison of numerical and analytical solutions of Eq. 7.

($U = 2 \text{ gal}/(\text{min} \cdot \text{ft}^2)$, $d_g = 0.5 \text{ mm}$, $\rho_p = 1.05 \text{ g}/\text{cm}^3$ and $T = 25^\circ\text{C}$). Adapted from Yao et al.⁸

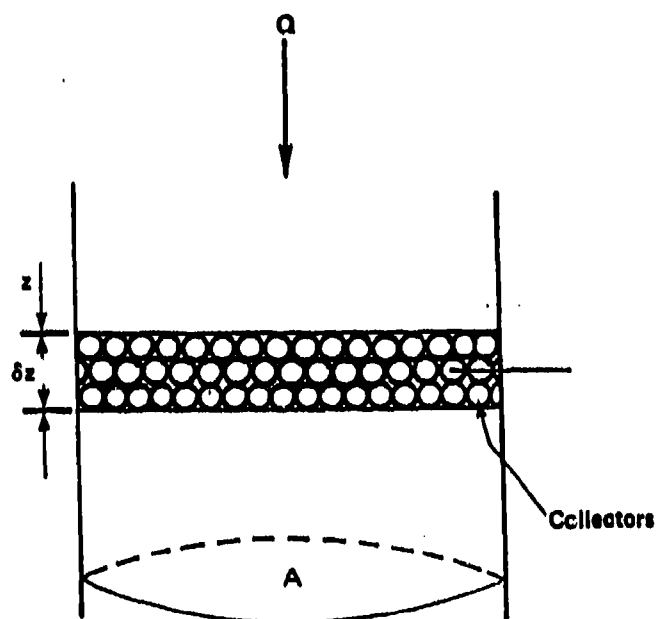


Figure 4. Differential volume element in the filter bed. (Q = flow rate, A = cross-sectional surface area).

Number of collectors = $(1 - \epsilon) A \delta z / V_g$, in which ϵ is the bed porosity, A is the total bed area, and V_g is the volume of a single collector. The rate at which all of the collectors contained in the filter bed are removing particles from the water is r_g (Eq. 2) times the number of collectors. The rate of removal per unit volume of all of the collectors, r_s , is

$$\begin{aligned} r_s &= r_g \times \text{number of collectors/volume of all collectors} \\ &= 3 \eta U n / 2 d_g . \end{aligned}$$

Also, the rate at which the particles are removed from the water per unit volume of the water, r_L , is

$$-r_L = \frac{(1 - \epsilon) r_s}{\epsilon} = \frac{U}{\epsilon} \left[\frac{3(1 - \epsilon) \eta}{2 d_g} \right] \cdot n . \quad (8)$$

The change in the particle-number concentration with depth at any time may be obtained from a material balance written about the differential element of bed volume of thickness δz shown in Fig. 4, or

$$(\epsilon A \delta z) \cdot r_L = Q \delta n$$

or

$$\lim_{\delta z \rightarrow dz} r_L = (U/\epsilon)(dn/dz) , \quad (9)$$

where $Q = \dot{U} \cdot A$. Substituting Eq. 8 into Eq. 9 gives

$$-\frac{dn}{dz} = \left[\frac{3(1 - \epsilon) \eta}{2 d_g} \right] \cdot n = \lambda n , \quad (10)$$

in which λ is the filter coefficient.

Yao et al.⁸ checked the validity of Eq. 7 with Eq. 10. The results of this comparison are shown in Fig. 5. The observed and theoretical minimum efficiencies were both located at a particle size of approximately $1 \mu\text{m}$, but the observed collector efficiencies were in general much greater than the theoretical. This means that the theory can be used to obtain a quantitative estimate of the particle size most likely to pass through a deep-bed filter, but only a qualitative estimate of the proportion removed.

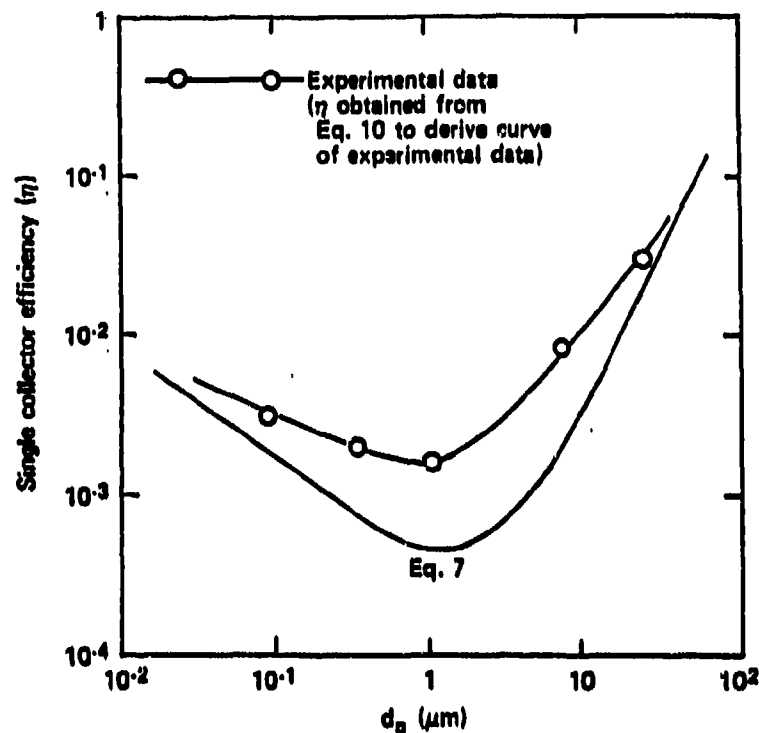


Figure 5. Comparison of observed and theoretical removals in a deep-bed filter. ($d_g = 0.397$ mm, $\epsilon = 0.36$, $U = 2$ gal/(min \cdot ft²), $T = 23^\circ\text{C}$, $z = 5.5$ in., $\rho_p = 1.05$ g/cm³, clean filter). Adapted from Yao et al.⁸

It was assumed in the previous discussions that all particles that strike or touch a collector will stick to the collector. This would be the case if all the suspended particles were completely destabilized. In general this is not the case and a parameter called the collision efficiency factor, α , is sometimes used to correct for a system of partially destabilized particles, or

$$-\frac{dn}{dz} = \left(\frac{3(1-\epsilon)\eta\alpha}{2d_g} \right) \cdot n. \quad (11)$$

The collision efficiency factor represents the ratio of the particles that stick to the collector to the total number of particles that strike the collector.

As stated in the assumptions, the single-collector theory was developed for the case of absolutely clean collectors. Filtration, however, is an intrinsically transient process because the particles deposited on the collectors change the geometry of the interstitial

spaces in the filter bed, as well as the nature of the collector surfaces.⁴ The deposited particles first act as additional collectors, but they eventually restrict the flow through the filter bed. Typically, an initial increase in the filter efficiency is observed, followed by a monotonic decrease.

The change in filter efficiency with the deposition of particles in the filter bed was investigated by Ives,³ among others. The following semiempirical expression was proposed for the filter coefficient, λ (Eq. 10):

$$\lambda = \lambda_0 [1 + (\beta_p \sigma / \epsilon)]^y \cdot [1 - (\sigma / \epsilon)]^z \cdot [1 - (\sigma / \sigma_u)]^x, \quad (12)$$

In which

λ_0 = filter coefficient for a clean bed

β_p = packing constant = $\frac{\epsilon}{1 - \epsilon}$

ϵ = bed porosity for a clean filter

σ = volume of particles deposited per unit bed volume

σ_u = ultimate value of σ when the filter bed becomes ineffective at a specified depth ($\lambda \rightarrow 0$ as $\sigma \rightarrow \sigma_u$)

x, y, z = empirical constants.

In Eq. 12 the first term, $[1 + (\beta_p \sigma / \epsilon)]^y$, gives the effect of the increase in specific filter surface (i.e., collector surface area per unit filter volume) available for deposition on the filter coefficient, which results in an initial improvement period. The second term, $[1 - (\sigma / \epsilon)]^z$, accounts for the decrease in the specific filter surface when the void spaces start to be filled. The third term, $[1 - (\sigma / \sigma_u)]^x$, gives the increase in interstitial-water flow velocity caused by the restriction in the flow passageways. Thus, the performance of a deep-bed filter will at first increase (the first term in Eq. 12 is predominant) and then deteriorate (second and third terms are predominant) with time. The durations of the initial improvement and the subsequent deterioration periods depend upon the relative magnitudes of the exponents x , y , and z . The pressure drop across the filter bed will always increase with time.

Particle Attachment

The transport model described in the previous section, albeit elegant, applies to the case of completely or nearly completely destabilized particles. It has little significance if the particles are not destabilized.

Whether or not a particle will stick to a collector is controlled by the surface properties of both the particle and the collector. According to O'Melia and Stumm,⁷ there are two significant models that have been used to describe the interactions between suspended particles and the filter media. The first model is based on the electrical double-layer theory. According to this theory, the solid side of a solid-liquid interface assumes an electrical charge, called the primary charge, which depends on the surface chemistry of the solid. An equivalent number of charges of opposite sign (secondary charges) form in the aqueous phase to counterbalance the primary charge. The counter charges are provided by the ions dissolved in the water, and such ions are called counterions. Because most clayey colloids, bacteria, cysts of protozoa, viruses, etc., carry negative primary charges, the counterions are usually cations. Some of the counterions are closely associated with the charged particles, and move with the particles when an electrical potential is applied to the colloidal solution. The net charge on the particle, including that of the closely associated counterions, determines a parameter called the zeta potential.

Theory demonstrates that if a particle with its associated zeta potential approaches another particle (or filter collector) with a zeta potential of the same sign, then an electrostatic repulsive force occurs between the particles that prevents a closer approach. If a strong electrolyte is added to the system, and especially if the electrolyte contains cations of high charge density, then the zeta potential will be depressed because the cations will be adsorbed on or near the solid surfaces. The particles may then collide when carrying sufficient kinetic energy to overcome the residual electrostatic repulsive forces. They will also stick together if the short-range van der Waals' attractive forces are greater than the repulsive forces at this proximity.

O'Melia and Stumm⁷ state that particle attachment brought about by charged synthetic or natural polymers (or polyelectrolytes), which have been successfully used as filter conditioners or coagulating agents in water treatment, cannot be characterized by the double-layer model. The model neglects the importance of chemical forces, such as coulombic attraction, when the suspended particle and the filter collector are of opposite charge, and it is only valid for lyophobic surfaces and simple electrolytes.⁷ The second, multifaceted theory, called the bridging theory, has been developed in recent years to explain interactions such as ion exchange, hydrogen bonding, and the formation of coordinative bonds and linkages that can outweigh electrostatic forces when polymer coagulation is used.

COAGULATION AND COAGULANTS

As shown in Fig. 1, a coagulant (or coagulants) is always added ahead of a deep-bed filter, regardless of the mode of operation. The coagulants most commonly used in the United States are alum [$\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$], hydrated ferric chloride ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$), and various nonionic or cationic synthetic polymers. A polymer is called a polyelectrolyte if the monomers from which it is synthesized contain ionizable groups. Cationic polymers gain a positive charge upon ionization, and anionic polymers gain a negative charge. Polymers that do not contain any ionizable groups are called nonionic.³ Research has revealed that both cationic and anionic polymers are capable of destabilizing negatively charged colloidal particles such as those found in natural waters, but anionic polymers usually have to be used in conjunction with another electrolyte such as NaCl or CaCl_2 , or with a coagulant such as alum.

Early investigations demonstrated that the double-layer theory alone did not adequately explain the observed mechanisms of coagulation with polymers. The chemical-bridging theory was then developed to explain the observed behavior.³ According to this theory, a molecule of an organic polymer or an inorganic polymer resulting from the hydrolysis of alum and ferric chloride will become attached to a colloidal particle at one or more sites. The number of sites occupied by a polymer molecule depends on the nature of the various electrostatic or chemical forces, and the charge and structure of the polymer and the colloid.³

A nonionic polymer, or even a polyelectrolyte having the same polarity as that of the colloid, may be adsorbed by the surface of the colloid. Some segments of the polymer molecule will be adsorbed by the surface, and some will extend into the solution phase. According to the bridging theory, those segments that extend into the solution, called loops and tails, form the bridges between the colloidal particles. There must be a minimum polymer size (i.e., minimum molecular weight) required to bridge the potential-energy barrier existing between two negatively charged colloidal particles.⁷

Cationic polymers can destabilize the negatively charged colloids commonly encountered in natural waters and wastewaters by both bridge formation and charge neutralization. As a result, cationic polymers do not require a minimum molecular weight to be effective since they can be adsorbed specifically by negative colloids and have their primary charge neutralized.³ Ghosh *et al.*⁹ state that studies of polymer configuration on colloidal surfaces by electron paramagnetic resonance have shown that cationic polyelectrolyte segments are often adsorbed almost completely by the particle surface without many loops or tails extending into the solution. This requires that a mechanism,

in addition to bridging, be operative, because the bridging mechanism depends on the presence of the extending segments. Those investigators concluded that charge neutralization plays an important role in cationic-polymer coagulation.

JAR TESTS

It appears from the foregoing that the destabilization of colloids with the cationic polyelectrolytes is achieved primarily by charge neutralization and interparticle bridging. Both of these mechanisms imply a stoichiometric reaction between the colloid and the coagulant, and both mechanisms may cause particle restabilization with overdosing.³ The theory of coagulation has not yet been sufficiently developed to determine the optimum coagulant dose or coagulant type that should be used in direct filtration; therefore, these determinations must be made experimentally.

The optimum coagulant dosage is most commonly determined by jar tests. The jar test is a laboratory method used to determine the effectiveness of various coagulants, optimum coagulant and coagulant-aid dosages, optimum pH for coagulation, and the most effective order in which the various chemical coagulants should be added to the suspension. The typical jar-test apparatus consists of six agitator paddles mechanically coupled to operate at the same speed, which can be varied from 10 to 100 rpm. The coagulation containers commonly are 1- or 2-L beakers. The general jar-test procedure consists of flash-mixing the chemicals by agitating at 100 rpm for 1 min, followed by flocculation at a stirring rate of 20 to 70 rpm for 10 to 30 min. The residual turbidity of the sample is measured after 30 min of quiescent settling.¹⁰

According to Benefield *et al.*¹¹ the optimum dose, as determined by jar tests, often does not match that observed in the treatment plant. One reason for this is that the jar test is a batch test, whereas the static flash-mixing tanks used in many water-treatment plants are continuous-flow devices that provide significant backmixing. A batch reactor is analogous to a plug-flow reactor and is inherently more efficient than a backmixing reactor for most reactions (Vrale and Jorden;¹² Benefield *et al.*¹¹); consequently, the dose of the coagulant required for the flash mixers in the treatment plant may be greater than that indicated by the jar tests.

This situation applies to the type of coagulant mixing presently used in the ERDLATOR of the MWPU. Agreement between jar tests and plant performance may be better for plants utilizing non-backmixing devices, such as that used in the 600-gph ROWPU, where rapid mixing is initiated in a pipe elbow and continued at a relatively high Reynolds number in the pipe leading to the multimedia filter.

Other tests used to ascertain the optimum coagulant type and dose include electrophoretic-mobility measurements (zeta potential) and more recently, particle-size-distribution analyses. Zeta potential is closely aligned with the simple double-layer theory of coagulation and hence is disparaged by those who believe that bridging plays the dominant role in cationic polyelectrolyte coagulation.⁷

INITIAL MIXING AND MEAN VELOCITY GRADIENTS

The aluminum and ferric iron contained in alum and ferric chloride, respectively, will generate positively charged polymer-like chains when given sufficient time and the appropriate water-quality characteristics. According to Weber,³ the hydrolysis and polymerization of these salts of Al(III) and Fe(III) are very rapid and require a uniform pH and coagulant concentration. The instantaneous blending of the alum and ferric-chloride feed solutions with the water is thus essential. The instantaneous blending of the high-molecular-weight organic polymers with the water is less essential because the polymers do not have to be formed within the system, and their rates of adsorption by the colloids are slower due to their larger size. Regardless of this distinction, it is apparent that the rate at which a coagulant is mixed with the raw water is nearly as important as the optimum coagulant dose. For example, the poor mixing of a polyelectrolyte with the water could result in an overdose on some of the suspended particles, and an underdose on others. The result would be poor coagulation, even though the average dose is correct.

The mean velocity gradient G (defined mathematically as the square root of $P/(V\mu)$, where P is the mixing-power input, V is the volume of water being mixed such that P/V is the power dissipation per unit volume, and μ is the dynamic viscosity of water)¹⁰ is commonly used to describe the intensity of mixing required in both chemical-mixing and flocculation devices. The greater the value of G , the more rapid the mixing rate for a device of a given geometry. This rule can not be extrapolated to devices of different geometries, as demonstrated by the results of Vrale and Jorden.¹²

Those investigators conducted some rapid-mixing experiments with different types of reactors, using alum as the coagulant. They employed one completely backmixed, stirred-tank reactor (CSTR) and four turbulent pipe-flow reactors of various geometries.¹² The efficiency of the coagulation process was determined by measuring the residual turbidity subsequent to a period of slow flocculation and sedimentation. An apparent turbidity-removal rate was then estimated from the observed turbidity values. Some of the results of their study are presented in Fig. 6.

The performance of the CSTR mixer (Unit 2) was the poorest, with the rate of aggregation actually decreasing when G was increased. It was also observed that the minimum mixing speed had to be greater than 150 rpm ($G = 350 \text{ s}^{-1}$) to achieve a uniform mixture in the CSTR. Unit 1, one of the pipe-flow reactors, provided a slow rate of blending and was used to determine the effect of the background mixing in the piping following the in-line turbulence inducers. The performance of Unit 1 is not depicted in Fig. 6. Unit 3, which had a complicated design and no practical application, was intended to serve as the standard of best performance, although this did not prove to be the case. Unit 4, a combination of Units 1 and 3, had a similar performance to that of Unit 3. Unit 5, which performed the best of all the mixing devices tested, consisted of an annular ring inserted in a round pipe. The ring had six holes for alum injection into the flow stream, with the holes facing downstream. Significant turbulence was created by expansion of the flow downstream from the annular ring.

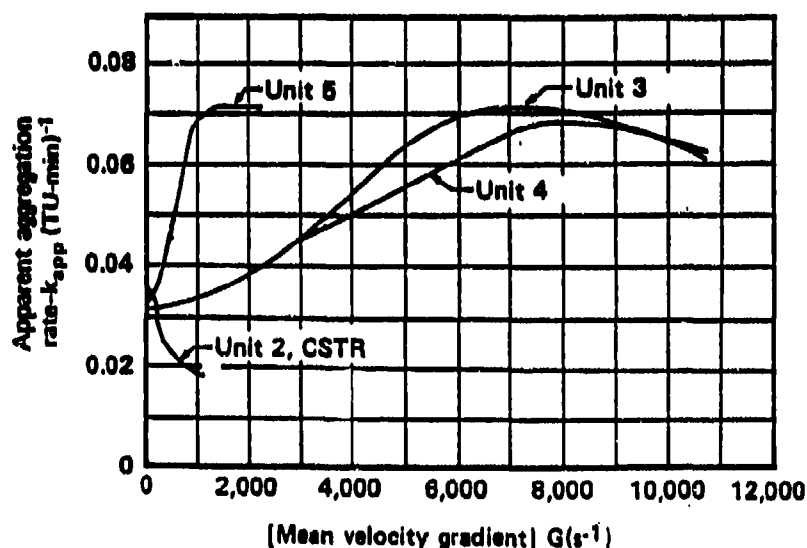


Figure 6. The effect of the mean velocity gradient, G , on the aggregation rate of suspended particles for rapid-mix devices of various geometries. Adapted from Vrale and Jorden.¹²

Vrale and Jorden¹² concluded that the completely backmixed stirred-tank reactor (CSTR) of the type often used in water-treatment plants provide the least satisfactory way of mixing two miscible fluids rapidly, and that G by itself is not a sufficient criterion for judging the rate of initial aggregation for devices with different geometries. The location of coagulant-application points and the turbulence intensity at and immediately

downstream from the chemical-addition points also should be considered. These researchers also indicated that an optimal design for colloid destabilization with alum would be optimal for destabilization with cationic polyelectrolytes because the particle-destabilization mechanisms are similar. This, in turn, is dependent upon the local and temporal concentrations of the coagulant and the colloids because the adsorption reactions are rapid and irreversible.

CARTRIDGE FILTERS

Cole et al.¹³ define a cartridge filter as a cylindrical object consisting of a disposable or cleanable porous medium, associated with an appropriate plastic or metal structure. Individual cartridges or multiples of cartridges may be installed in a filter housing. In most instances, cartridge filters are required to remove particles of size ranging from fractions of a micrometer to 40 μm (Warring¹⁴ gives this size range as 1 to 500 μm), and they are used in many industrial applications. Materials such as cotton, wool, rayon, cellulose, fiberglass, polypropylene, acrylics, nylon, asbestos, etc., or various combinations of these materials, are commonly used as filter media in the disposable cartridge elements. Materials such as stainless steel, Monel alloys, and ceramics are used in the reusable filter elements.

Cartridge filters are classified into two categories, "depth" and "surface" filters. Depth-type filters capture particles throughout the total thickness of the medium within the interstices of the internal structure.¹³ These filters normally have a structure that gradually increases in density toward the center of the element.¹⁴ Thin media, such as paper or woven-wire cloths are described as surface-type filters because most of the particle capture occurs at or near the filter surface. According to Cole et al.,¹³ the terms "surface" and "depth" are relative rather than absolute because removals vary considerably with the size and chemical properties of the suspended particles, the rigidity of the medium, the uniformity of the element pore sizes, and the thickness of the medium.

The absolute size rating of a cartridge filter is defined as the largest hard spherical particle that will pass through the filter under specified conditions, or sometimes the largest opening in the filter.¹³ The "nominal" size rating is a term used by the military and is defined by a test apparently used only by the military.¹³ Increments of a fine test dust are introduced upstream from the filter. Small portions of the filter effluent are then examined microscopically for particle counts. The counts are converted mathematically to weight values, and the size at which 98% of the particles by weight is retained on the filter is called the "nominal size". The test does not give reproducible results and has never been widely accepted.¹³

DIATOMACEOUS-EARTH (PRECOAT) FILTERS

A precoat filter consists of a rigid, semiflexible, or flexible septum (or screen) on which filter aid (or medium) is deposited.¹⁴ Usually a filter system consists of several septa which are housed in a pressure vessel. Each of the septa supports a thin layer of filter aid that has been deposited hydraulically on one side of the septa at the beginning of the filtration cycle; this thin layer is called filter cake.

The screen or the septum on which the aid is formed is basically a strainer, and the principal mechanism involved in the removal of the solids is believed to be mechanical straining or direct interception.¹⁴ The septum, the filter cake, and the particles which are filtered from the raw water all contribute to the straining of additional suspended particles from the water being filtered. In straining, particles larger than the pore size of the filter cake are collected on the upstream surface of the filter. Adsorptive forces also provide a small positive contribution to the removal of suspended solids. The adsorptive forces arise from the nonuniformity of the upstream surface of the filter, which results from the fact that the pores are not uniform in shape or direction and the surface is not perfectly smooth.¹⁴

The desired properties of the precoating filter aid are that it be a finely divided powder, light weight and insoluble in the liquid to be filtered. The aid should have no effect upon the chemical properties of the filtrate, and should be fine enough to remove essentially all of the suspended solids.

The filter aid used in most precoat filters is manufactured from diatomaceous earth, which consists of the siliceous fossil remains of dead aquatic algae called diatoms. The diatoms are processed by crushing, calcining (heating to a high temperature without fusing), and classification to yield a fine, porous, multishaped, angular media, ranging in size from about 5 to 50 μm . Processed diatomite filter aid has the required characteristics for water filtration. The structure permits the formation of a rigid, porous (>90% porosity) filter cake that will retain solids well as the water or other liquid containing those solids passes through the filter. Perlite, which comes from a siliceous rock, is another material which can be used in precoat filters.¹⁵

The clarifying ability is the parameter used to characterize the performance of diatomite filter aid. The number that quantifies this ability is called the "clarity index"; it is inversely proportional to the permeability of the aid. Thus, as the permeability of the diatomite increases to allow more throughput, its clarifying ability decreases and larger suspended solids pass into the filtrate.

The precoat filtration run or cycle consists of four steps¹⁶: (1) a thin layer of filter aid is applied to the septum to form the filter precoat; (2) the water is filtered until a predetermined pressure drop across the filter is reached; (3) the fouled filter aid is expelled from the filter elements by backwashing; and (4) the water in the filter shell containing the backwash sludge is released to waste.

Precoat filter aid is applied in one of the two following ways: (1) the aid is applied directly to the filter septum by filtering water containing the aid at the start of the run, or (2) a previously prepared filter-aid slurry is recirculated through the filter until the filter effluent returning to the slurry tank is clear. Generally this precoat has a thickness of 1/16 to 1/8 in. The procedure to be used should be selected according to the porosity of the septum and the fineness of the filter aid. The recirculating procedure is advantageous when the septum openings are large and the filter aid is fine.¹⁶

As water containing suspended particles is filtered during a filtration run, the precoat-cake surface gradually becomes fouled with a layer of particles. This increase in the thickness of the filter cake will result in clogging of the filter and an increased pressure drop across the filter. This effect can be mitigated to some extent by continuously injecting small amounts of filter aid into the raw water as it enters the filter, which helps to maintain a highly porous filter cake. This additional filter aid is called body feed.

The total filter-aid requirement includes the amount of material used to precoat the septa, as well as that added as body feed. The optimal amount of precoat material to be used in any filter will be the minimum amount needed to protect the filter element from clogging while producing an effluent of the desired quality. In general, body-feed requirements vary in proportion to the raw-water turbidity, although the type of suspended solids also affects the amount of body feed required.¹⁶

If the primary mechanism of suspended solids removal with diatomaceous earth filtration is straining, then it follows that the removal of suspended solids is a function of the particle size of the filter aid. Tien and Payatakes⁴ state that straining is effective when the size of the particles is greater than 0.2 times the filter-grain size. Cheremisnoff and Azbel¹⁵ state that diatomaceous-earth filter aids have good efficiency in retaining particles of sizes less than 1 μm . Warring¹⁴ does not give a quantitative measure for particle size but states that diatomaceous-earth filter aids can provide extremely fine filtering and are used frequently when very high purity is required, such as in the filtering of sugars, edible oils, or water. The particle size of commercially available diatomaceous-earth filter aids ranges from 5 to 50 μm .

Prior to filtration, the raw water to be filtered may be coagulated, flocculated, and allowed to settle. However, all, some, or none of these three processes may be used; the choice will be made based on the raw-water quality.

The modes of filter operation shown in Fig. 1 for deep-bed filters apply equally well to precoat filters. The term direct filtration is also used for precoat filters when the coagulated water is not settled prior to filtration.

DESCRIPTION OF THE 600-GPH ROWPU PRETREATMENT SYSTEM

According to Carnahan *et al.*,¹⁷ a conventional clarification system with separate coagulation-flocculation and sedimentation basins could not be used in the 600-gph ROWPU pretreatment system because of restrictions imposed by the U.S. Army on the overall dimensions of the ROWPU. Instead, the pretreatment used consists of direct filtration by a multimedia pressure filter with in-line polyelectrolyte addition, followed by processing through a cartridge-filtration unit. This pretreatment, aside from the cartridge unit, is somewhat in accord with scheme C in Fig. 1, except that a cationic polyelectrolyte is used in lieu of the alum, activated silica, or nonionic polymer, and the filtration rate is $7 \text{ gal}/(\text{min} \cdot \text{ft}^2)$, instead of the $5 \text{ gal}/(\text{min} \cdot \text{ft}^2)$ shown in the scheme.

As shown in Fig. 7, the multimedia filter removes solids that pass through the input-water strainer, as well as the smaller solids that are acted upon by the coagulant.¹⁸ A cationic polyelectrolyte and sodium hexametaphosphate are added ahead of the multimedia filter. Citric acid is added after the multimedia filter and before the cartridge-filter unit according to Fig. 7.^{18,19} Sodium hexametaphosphate and citric acid are added primarily to control the rate of RO membrane fouling. The citric acid is added in quantities sufficient to adjust the water pH to a value between 5 and 8.¹⁸ Chlorine is added after the RO unit to prevent chlorine from damaging the membrane elements.

Carnahan *et al.*,¹⁷ state that the multimedia filter was designed to operate at rates ranging from 5 to $10 \text{ gal}/(\text{min} \cdot \text{ft}^2)$ because this range provides the optimum trade-off in size versus filtration efficiency. The nominal filtration rate is stated¹⁸ to be $6.5 \text{ gal}/(\text{min} \cdot \text{ft}^2)$, which is equivalent to a total ROWPU feed-water flow of 32 gal/min.

COAGULATION

The cationic polyelectrolyte, Cat-Floc T1 (manufactured by Calgon, Pittsburgh, PA) is used in the ROWPU pretreatment system.¹⁷ It is pumped to the filter-feed line with an American Lewa positive-displacement pump with a 200-mL/min capacity. According to

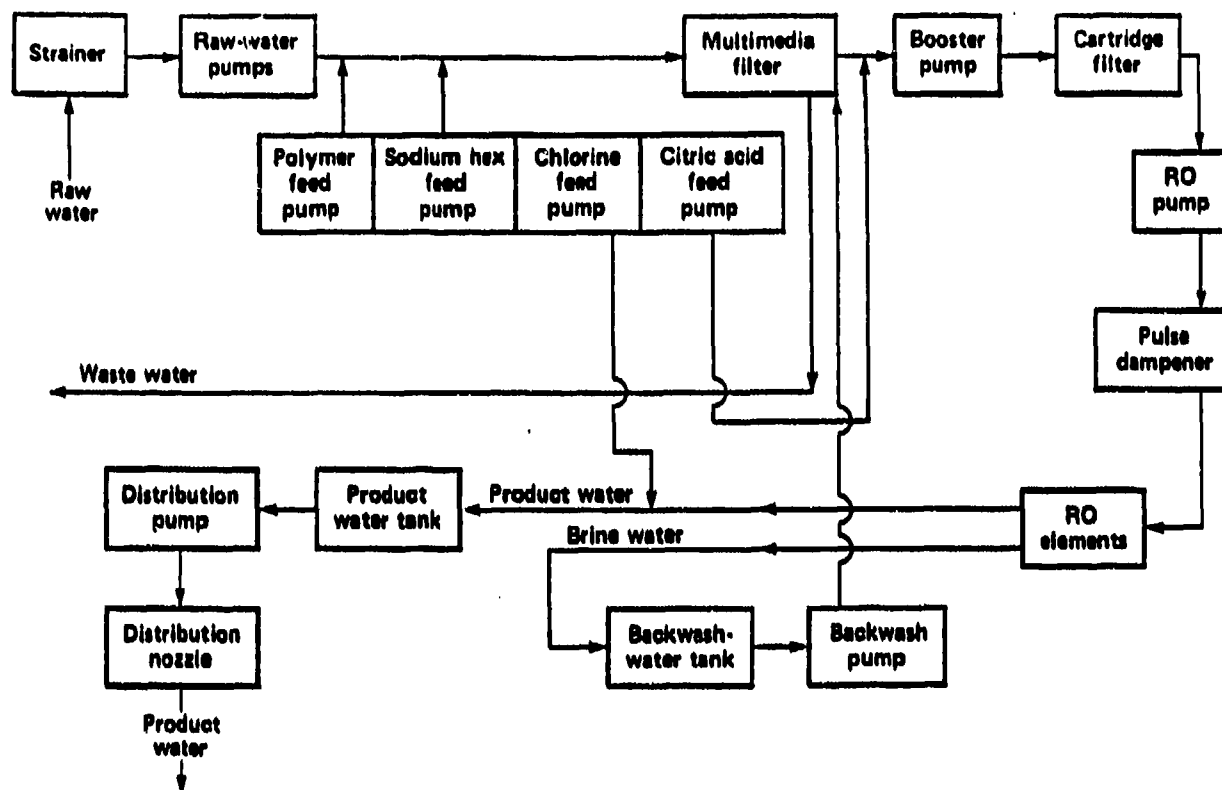


Figure 7. Water-processing block diagram for the 600-gph ROWPU. From TM 5-4610-215-10.¹⁸

the 600-gph ROWPU operator's manual,¹⁸ the chemical feed pump is calibrated to a flow rate of 60 mL/min, which corresponds to a dosage of 5.2 mg/L for the nominal ROWPU flow rate.

The chemical-feed flow rate is adjusted during operation to improve the performance of the multimedia filter if necessary. This is achieved by using a turbidity tube, the bottom of which contains a white bull's-eye set in a black background disk. A 600-mL filtered-water sample is drawn into the tube from the cartridge-filter drain. The criterion for water clarity is that both the white bull's-eye and the black disk at the bottom of the tube should be seen clearly. If both are not visible, the polymer dosage should be altered. This is accomplished by changing the chemical-feed flow rate. The U.S. Marines adjust the dosage in accord with the 600-gph ROWPU operator's manual.¹⁸ It is uncertain what operating procedure is followed by the U.S. Army.

Carnahan *et al.*,¹⁷ state that the ROWPU chemical-feed system provides a mean velocity gradient of 300 s^{-1} for approximately 0.1 s and 800 s^{-1} for 2 s. This was checked for a total-flow rate of 34.5 gal/min and a 2-in. i.d. multimedia filter feed-water pipe 6 ft long with two right-angle elbows. The mean velocity gradient G was estimated

to be approximately 3000 s^{-1} for the elbow where the coagulant is injected, and approximately 800 s^{-1} for the pipe. The residence time for the pipe was about 2 s. These numbers check well with those reported by Carnahan *et al.*,¹⁷ except for the discrepancy in the G value at the elbow.

MULTIMEDIA FILTER

The multimedia filter in the 600-gph ROWPU is a pressure filter (Culligan mixed-media filter) operated under a nominal pressure of 30 psig.¹⁷ The dimensions and characteristics of the media installed in the filter are given in Fig. 8. The minimum operating pressure is reported to be 25 psig.¹⁸

The backwash-water system for the multimedia filter is shown schematically in Fig. 9.¹⁸ Brine from the RO elements is used as the backwash water. The backwash pump is a centrifugal pump with a maximum capacity of 120-gal/min water flow and 70-psig pressure and is controlled by a gate valve as shown in Fig. 9. The backwash system, which is provided with a timer, operates automatically. The backwash operation lasts approximately 20 min after the backwash pump is started. During backwash, the water-flow rate varies automatically from 0 to between 70 and 120 gal/min (0 to between 14 and 24 gal/(min \cdot ft²)) while washing and rinsing, which fully fluidizes the multimedia bed.^{1,17,18} According to the operator's manual, the filter should be backwashed after 20 h of operation or when the filter pressure drop exceeds the initial drop by 5 psi. The initial pressure drop is usually about 2 psi.¹⁷

Carnahan *et al.*,¹⁷ give the results of some ROWPU multimedia filtration tests, from which it was estimated that the filter retained approximately 3300 g of solids just before backwashing was required. It was also observed that, by using two backwash cycles of 15 and 24 gal/(min \cdot ft²), the filter was cleaned sufficiently to regain the initial pressure drop of 2 psi.

ROWPU CARTRIDGE FILTERS

The effluent of the multimedia filter is polished with 5- μm nominal size rating cartridge filters.¹ (The definition of nominal is given in the section entitled Cartridge Filters). The purpose of this unit is to prevent the carry-over of solids or organics to the reverse osmosis (RO) components.¹⁷

Eight replaceable filter elements are housed in a single pressure vessel as illustrated in Fig. 10. The filter elements consist of polypropylene cord woven around stainless steel cores. The water flows in a spiral motion around and into the stainless steel core, and

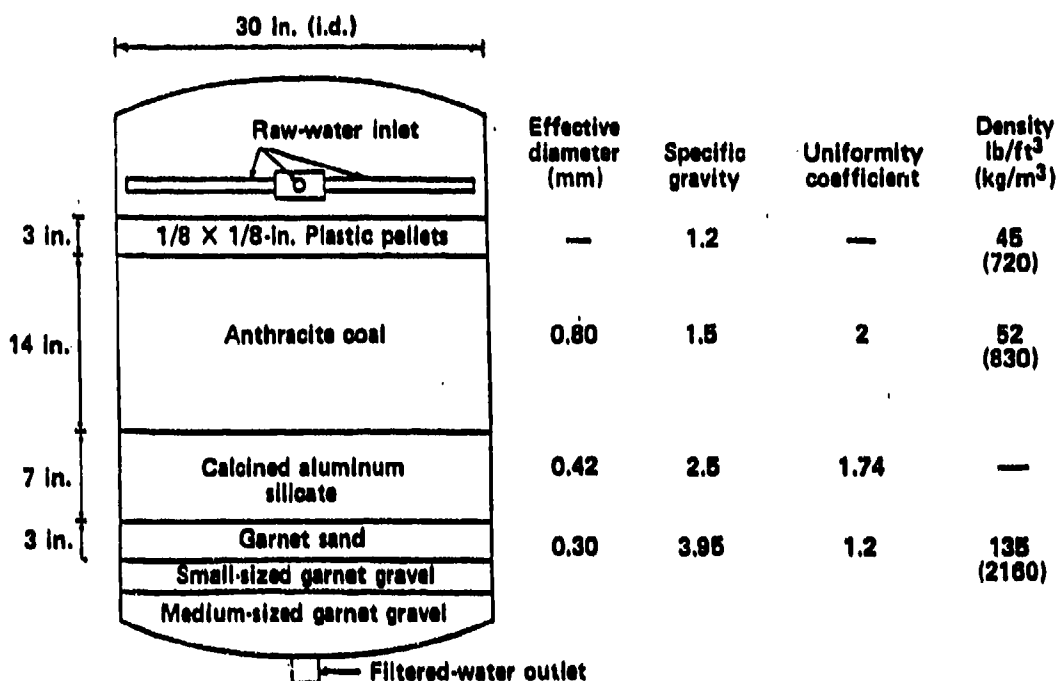


Figure 8. ROWPU multimedia filter. From Small *et al.*¹

then out of the bottom of the pressure-containment vessel. The filter elements are classified in the group called "depth" filters with high contaminant-holding capacity.²⁰ The tubular elements are 40 in. long and 2-3/4 in. in diameter, which gives a surface area of 2.4 ft² per element, or a total of 19.2 ft² per installation.²¹ The filtration rate is thus 1.8 gal/(min • ft²) (14.4 m/h) for a ROWPU flow rate of 34.5 gal/min.

According to the manufacturer of the cartridge-filter elements (Filterite Corporation, Timonium, MD), the polypropylene filter media is compatible for use with strong acids and concentrated bases, and at temperatures up to 275°F (135°C). Polypropylene, however, is affected by oxidizing agents such as free chlorine. This may inhibit or exclude prechlorination of the raw water if the 600-gph ROWPU is to be operated in the bypass mode (i.e., by-passing the ROWPU RO section).

DESCRIPTION OF THE MOBILE WATER PURIFICATION UNIT

A Mobile Water Purification Unit (MWPU) was developed and tested by the Engineering Research and Development Laboratory (ERDL) at Fort Belvoir, Virginia. The development of this equipment was the U.S. Army's response to a need for a lightweight,

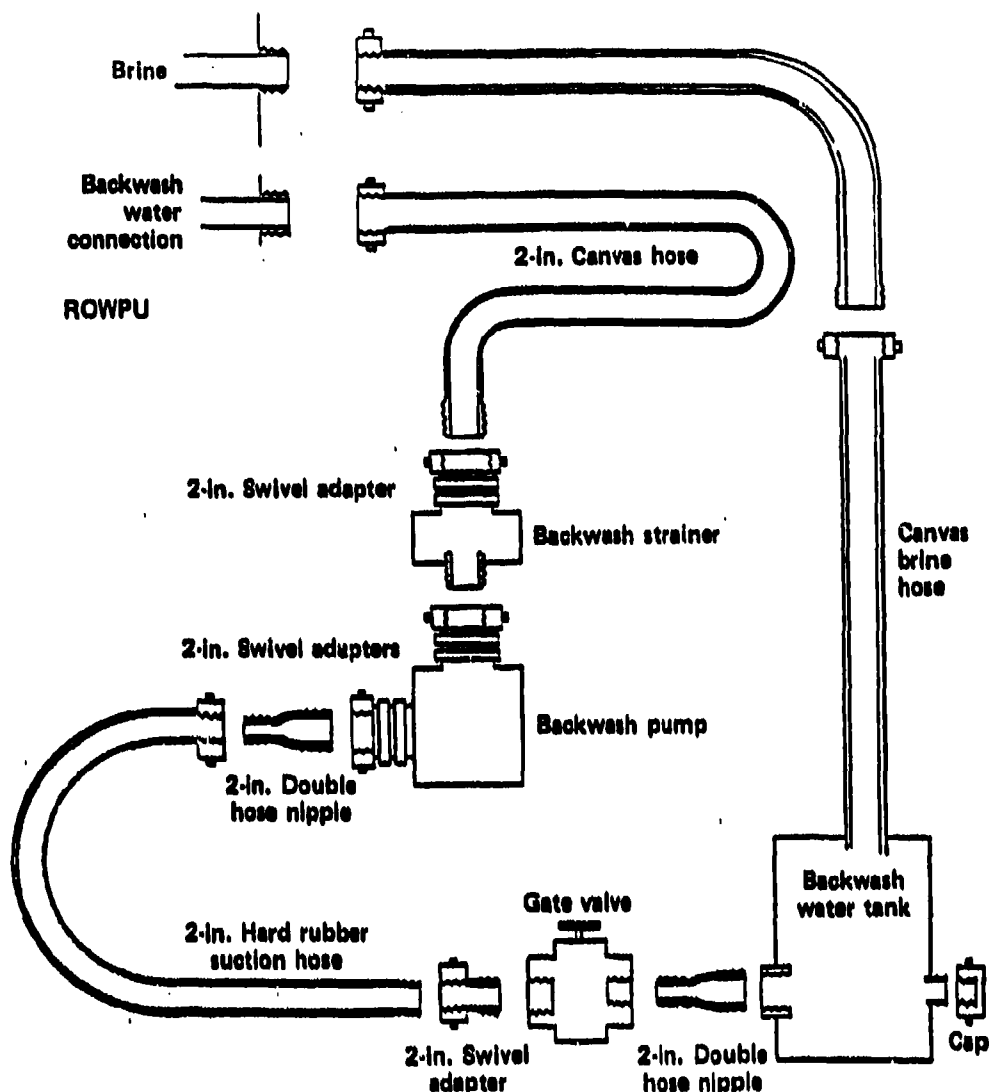


Figure 9. The backwash water system for the 600-gph ROWPU multimedia filter. From TM 5-4610-215-10.¹⁸

mobile system that was reliable and capable of producing potable water for field troops in a variety of hostile environments. Concern was focused on operation with cold water, and the equipment was designed for freshwater point sources.

BACKGROUND

Water fit for drinking is now used by the field Army for drinking, bathing, kitchen tasks and laundry. If local water-treatment facilities are not available, then raw fresh waters must be treated by field equipment to provide for these needs. The equipment must be reliable and capable of treating water from almost any surface source. While the

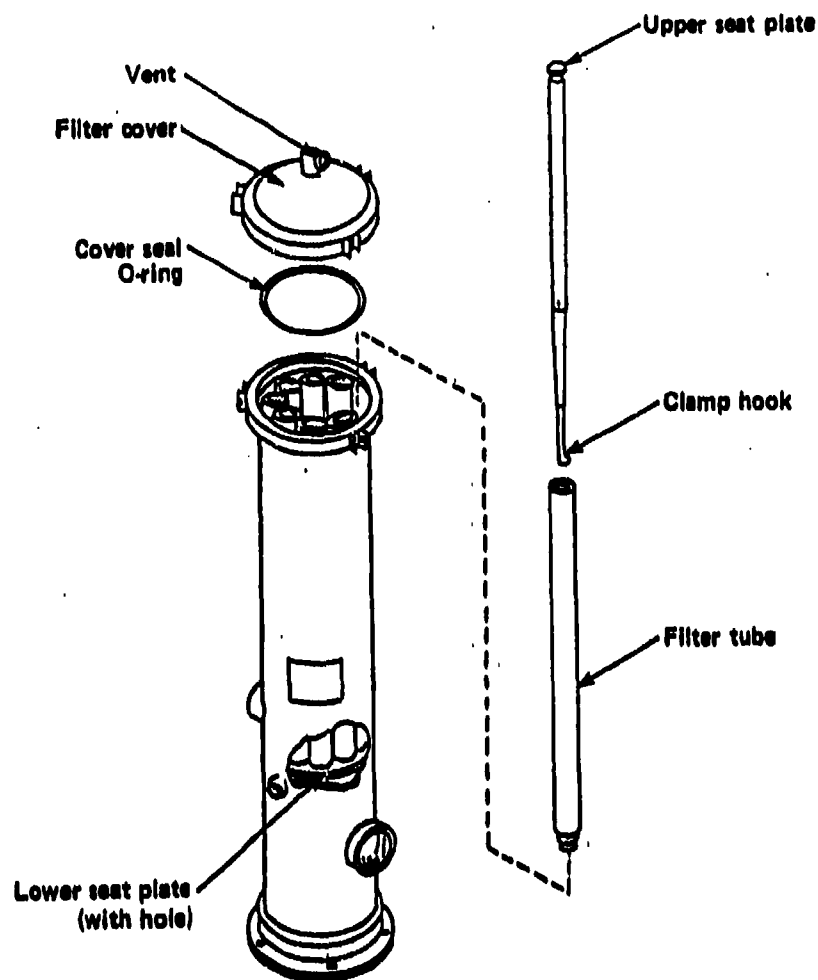


Figure 10. Diagram of the 600-gph ROWPU cartridge filter. From TM 5-4610-215-10.¹⁸

water points are checked by the Medical Corps for suitability, easily treatable water is not always found, and the equipment may be called upon to purify waters that are turbid, colored, polluted with natural biological pathogens, or have extreme pH values. Nuclear, biological, and chemical warfare agent removal is also a concern.²²

The terrain and weather conditions in which the water treatment is to take place are unlikely to be kind to the equipment. For example, the equipment will be used in isolated locations where the only protection for the unit is that which is actually part of the unit itself. It must be capable of operating at high and low ambient temperatures, in rough terrain, in rain, sleet, high winds, and at night. The equipment may be moved on short notice, and should be self-contained so that it can be started up soon after arrival at the next water point. Because the troops often must operate the equipment under adverse conditions, it should be simple to operate and rugged. Moreover, a minimum number of troops should be required to operate it.

The development of the Mobile Water Purification Unit (MWPU) began in 1949, and testing was completed in 1955. This work was conducted by the U.S. Army in conjunction with special studies performed by institutions funded by the Army. All three processes used for water treatment in the MWPU were studied: (1) coagulation and clarification, (2) diatomaceous-earth filtration, and (3) disinfection. Research projects were funded at Harvard University on water-disinfecting agents, at New York University on water-coagulation procedures, at the University of Illinois on filter septa and water filterability, and at Johns Hopkins University on filter aids. The Sanitary Engineering Branch of ERDL conducted basic research and development efforts on related studies.

Two prototype water-purification units were tested using the solids-contact clarifier, filters, and disinfection processes. Field operations were carried out at sites at Lake Michigan in Illinois, at several lake and river sites in southern Virginia, and at the Potomac River site of ERDL at Fort Belvoir, VA. Fifty hours of operation were logged at each site. The two test models used were similar, except for the solids-contact clarifier. One had an Army-designed clarifier and the other an off-the-shelf commercial clarifier, which could serve the same function as the Army model.²³

The results of these tests gave U.S. Army designers the criteria to be used for equipment having the required military characteristics. They decided what design modifications should be made to accommodate the high and low ambient temperatures in which the equipment would be operated, and they recommended that the "Water Purification Unit, Mobile, Electrified, 1500-GPH Capacity" should be designed and fielded. They also recommended the expansion of the project to include development of a 3000-gph capacity model.²³ Most data on MWPU performance have been published for the 3000-gph model.

TREATMENT SYSTEM

The MWPU with supporting equipment in place is illustrated in Fig. 11. A cutaway view of the processes contained in the truck-mounted van is shown in Fig. 12. The treatment processes consist of the following: solids-contact clarification; disinfection with calcium hypochlorite; external solids concentration; and diatomaceous-earth filtration. The solids contact clarifier, designed at ERDL, is called the ERDLATOR. The rate at which the water is treated by the MWPU is controlled by the hydraulic loading on the ERDLATOR. The MWPU is fielded in three versions, 600, 1500, and 3000 gph.

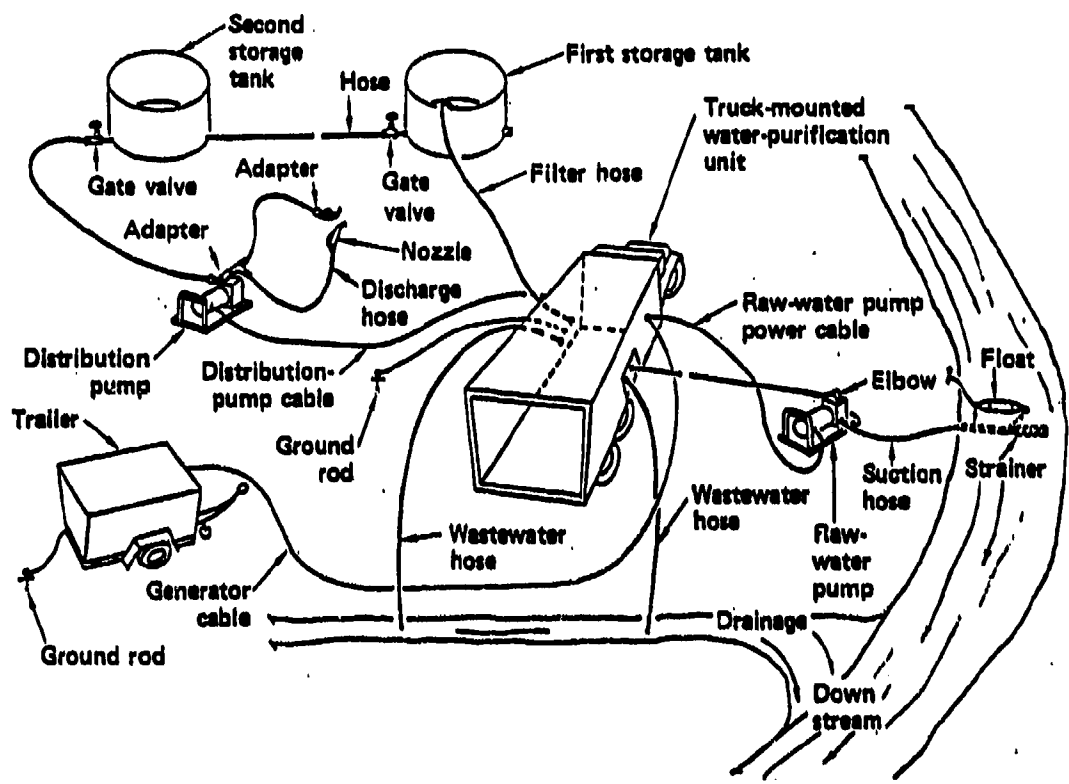


Figure 11. The 1500-gph MWPU and supporting equipment in operating position. From TM 5-4610-218-12.²⁵

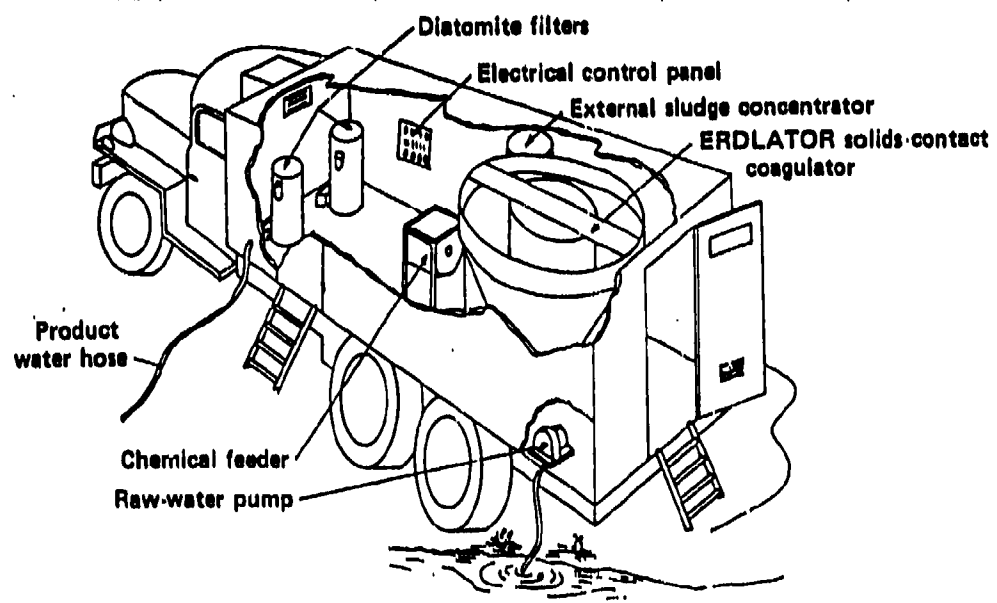


Figure 12. Cutaway view of Mobile Water Purification Unit. Adapted from Ruiz and Schmitt.²³

The raw water is pumped to the clarifier with a self-priming, 2-hp centrifugal pump. Large debris is excluded with a strainer installed on the suction hose as shown in Fig. 11. The effluent from the ERDLATOR is pumped through two diatomaceous-earth filters. The filter effluent then flows by gravity to two 3000-gal capacity storage tanks in series. The treated water is pumped by a second self-priming, 2-hp pump from the second storage tank to the distribution system. Wastewaters from the system, which include the concentrated sludge derived from the ERDLATOR, as well as the backwash of the filters, are released by gravity to a discharge point located downstream from the raw water intake. Normally, the equipment can be installed in less than one hour by three soldiers and routinely operated by one.²⁴

The van-type body used to hold the treatment units for the 3000-gph model is 258 in. long, 98 in. wide, 88 in. high, and is carried on a 2.5-ton truck.²⁵ The van interior is insulated and heated. When the unit is operational at temperatures between 0 and -40°F, a gas-burning heater is used to warm the treatment system;²⁶ other heating devices may be used to prevent freezing of the effluent in the distribution system. The shipping weight of the van is 9400 lb. The total weight is much greater when operating, due to the weight of water being processed; the van is leveled and supported by four jacks mounted on the van frame.²³

All the required power is supplied by a military standard 10-kW generator that weighs 1500 lb. Fifty feet of insulated power cable is used so that the generator may be operated remotely from the water-purification unit, thereby minimizing the noise to which the operators are subjected. The generator is skid-mounted and transported on a 1.5-ton cargo trailer.

The ERDLATOR

Figures 13 and 14 present cross-sectional and three-dimensional views, respectively, of the ERDLATOR used in the MWPU. The raw water is first metered and then introduced into two small mixing launders located above the flocculator. Dissolved gases that may be supersaturated in the feed water are removed to a considerable extent in these chambers by water forced through four aspirator nozzles, as shown in Fig. 14.

Solutions of calcium hypochlorite, ferric chloride, and pulverized limestone slurry are all added to the water in the influent launders in the production model of the ERDLATOR. (Figure 13 indicates the addition of chemicals at different points in the apparatus; this was the mixing arrangement used in the prototype model.) The arrangement used to add the coagulant (ferric chloride) to the water makes calculation of the mean velocity gradient G impossible.

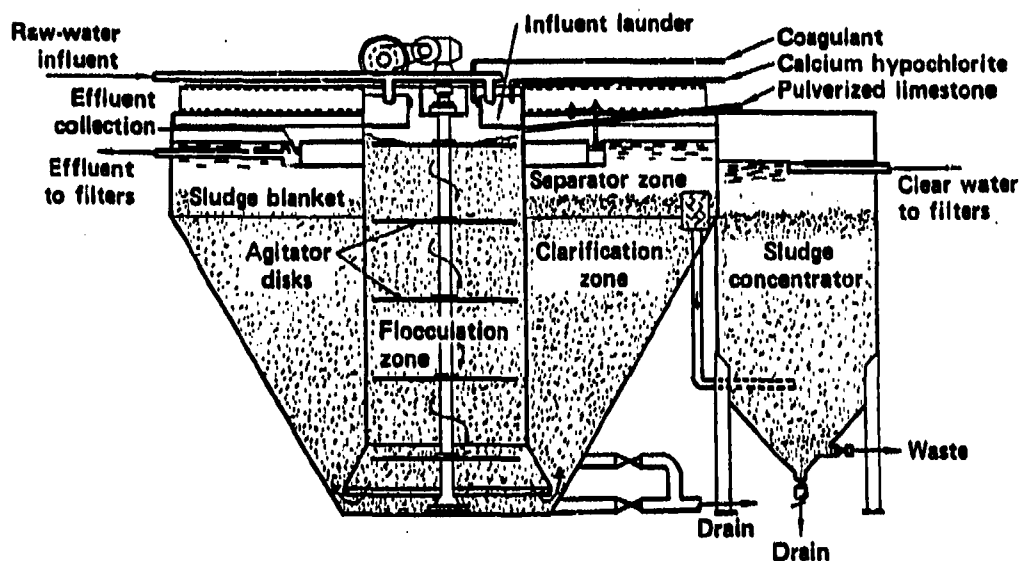


Figure 13. Cross-sectional flow diagram of ERDLATOR (original testing version). Adapted from Ruiz and Schmitt.²³

From the launders the water then passes to the cylindrical flocculation chamber, which is separated into three or more sections with horizontal, flat-metal disks. The disks are attached to a vertical hollow shaft and are spaced equally along the shaft. The disks serve to divide the chamber into compartments, thereby shortening the required mixing time and avoiding major opportunity for short-circuiting. The shaft is rotated at about 100 rpm to provide velocity gradients for the flocculation process. This agitation also serves to detach gas bubbles from the solids. The gas can escape either through holes drilled in the disks or in the hollow shaft. The mixing chamber contains approximately 40% of the total volume of 930 gal held in the ERDLATOR tank of the 3000-gph MWPU. This gives a mean flocculation time of about 7-1/2 min. The flat-metal disks have an edge velocity of 24 ft/s at 100 rpm.²⁶

The water leaving the flocculation chamber is directed vertically upward in the solids contact clarifier by shallow baffles that reverse the rotation of the water as it leaves this chamber. A well-defined ferric chloride-limestone slurry sludge blanket is formed in the clarifier, as indicated in Fig. 13. The excess sludge is drawn off at a point located about 10 in. below the circular dual-edge collector weirs. The waste sludge is allowed to concentrate by gravity in a separate sludge concentrator, as illustrated in Figs. 13 and 14.

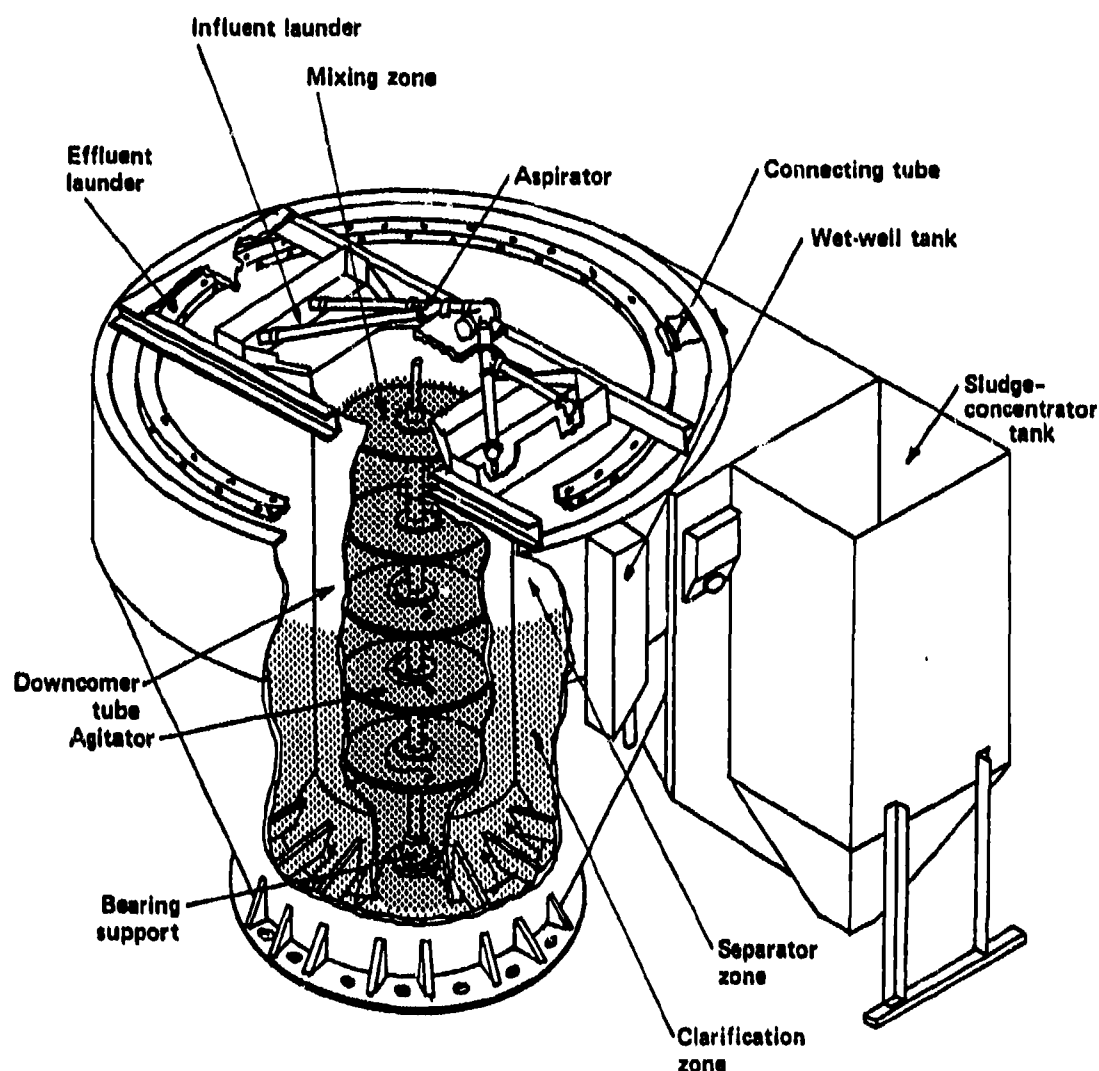


Figure 14. Cross section of the 1500-gph MWPU (ERDLATOR) assembly. Adapted from TM 5-4610-218-12.²⁵

The vertical upflow water velocity in the clarification zone is about 3 ft/min ($1.22 \text{ gal}/[\text{min} \cdot \text{ft}^2]$) at the section of maximum horizontal area for the 3000-gph model. It was recommended that this "rise velocity" should be reduced for water temperatures below 40°F to allow for floc formation. The total mean residence time in the ERDLATOR including the flocculation zone is about 20 min. The turbidity of the effluent typically ranges in value from 0.5 to 2.0 turbidity units.²²

The effluent from the ERDLATOR, together with the clear supernatant from the sludge concentrator, flows to a wet well. The water is then pumped to the diatomaceous-earth filters. A float operated valve triggers a switch to notify the operator if the wet-well level drops too low.

Conditioning Chemicals

Ferric chloride, the primary coagulant used in the ERDLATOR, is dissolved in water and is pumped to the ERDLATOR with a dual-sided electrical diaphragm pump. The dose applied is commonly in the range of 50 to 75 mg coagulant/L feedwater.²²

A slurry of the pulverized limestone is prepared in a small dual-compartment slurry feeder. The tank contains agitators that revolve vertically. Measuring cups attached to the agitators convey the chemical to a funnel leading into the slurry tank. The feed rate is controlled by hand, and the amount of chemical to be added is determined by the soldier on duty. Commonly, the limestone dose rate varies from 50 to 150 mg of limestone per liter of influent feed water.²² The same slurry feeder is used to prepare the diatomaceous-earth body coat for the filters. The slurries are pumped to the ERDLATOR or the filters with a pump located inside the slurry tank.

The pulverized-limestone particles tend to become enmeshed with and add weight to the floc particles formed by the ferric chloride coagulant. In their research work, the U.S. Army found in many different test situations that the use of pulverized limestone brought stability to the coagulation process and provided water of relatively uniform quality in the effluent. Limestone also provides some protection against low-pH waters. The enhanced sludge-blanket stability also makes it possible to bring the MWPU on-line quickly.²⁷

A solution of calcium hypochlorite is prepared and pumped to the ERDLATOR with one side of the dual-sided diaphragm pump, which is also used to pump the ferric chloride solution. This disinfectant also increases the rate of coagulation. The dosage is adjusted by the operator to give the same total-residual chlorine in the fully treated potable water as that specified by medical personnel. Equipment and chemicals are available for determination of either free-residual or total-residual chlorine. Typical doses of calcium hypochlorite range from 3 to 7 mg/L.²²

Powdered activated carbon may also be added to control strong tastes and odors. The carbon is applied in the mixing zone of the ERDLATOR at the same point as the ferric chloride, calcium hypochlorite, and pulverized limestone. The activated-carbon dose recommended for this treatment is 2 to 10 mg/L.²²

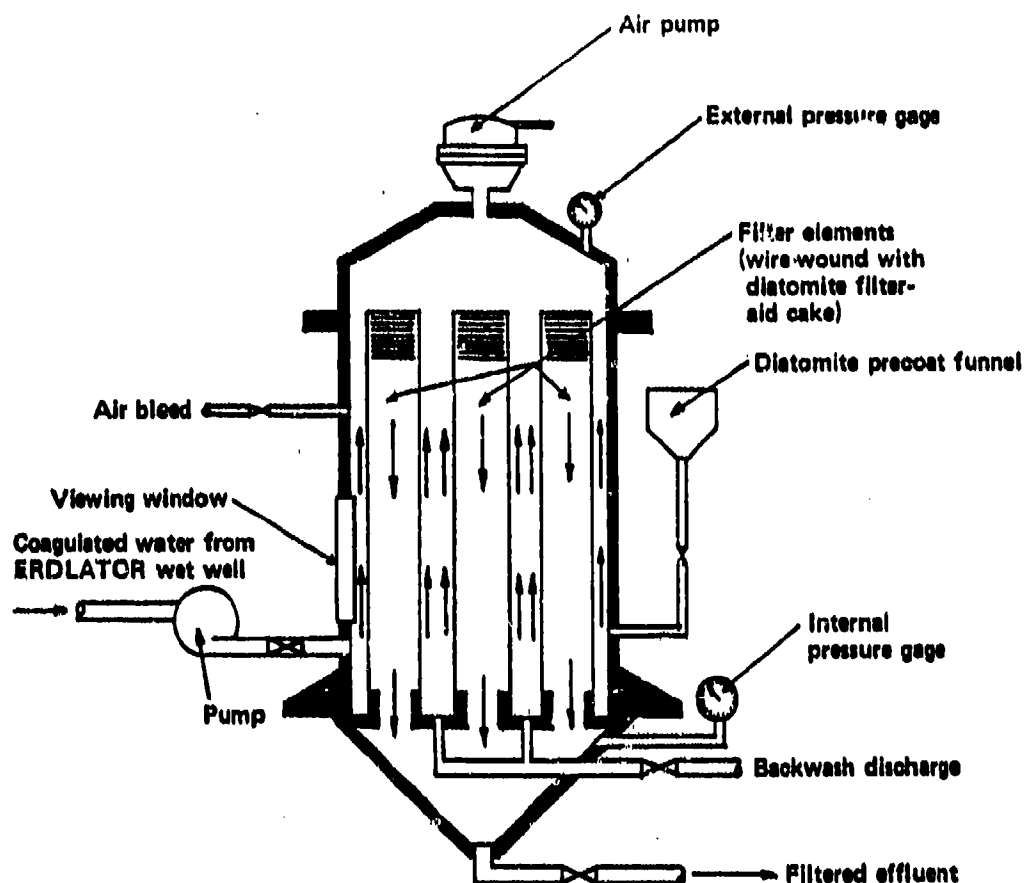


Figure 15. Cross section of diatomite-filter, final testing device for use in the Mobile Water Purification Unit. From Donahew.²⁸

Precoat-Filter Operation

The water stored in the ERDLATOR wet well is pumped by a centrifugal pump to the diatomaceous-earth filters, as illustrated in Fig. 15.²⁸ The water enters the vertical cylindrical shell of the filters under pressure and is forced through six diatomaceous-earth filter elements. The filtered water then flows by gravity to two 3000-gal storage tanks arranged in series. The total effective surface area of the filter elements is 10 ft^2 for each of the two filters.²⁴

The wire-wound filter elements are precoated with a slurry of diatomaceous earth. Diatomaceous earth is also added continuously to the influent water to give longer filter runs.²⁵ A controller installed on the filtered-water line is used to control the flow rate through the filter element. The maximum filtration rate permitted by the controller is $3.0 \text{ gal}/(\text{min} \cdot \text{ft}^2)$ and the nominal rate is $2.5 \text{ gal}/(\text{min} \cdot \text{ft}^2)$ for a 3000-gph production rate.²⁴

Eventually the pressure drop across the filter elements builds up to such an extent that the filter cake and captured solids must be removed and the filter elements recoated. This is accomplished by the "air-bump" method. Air is trapped in two places in the filter housing during a filter run, and the pressure on the filter elements is relieved almost instantaneously when the air-relief valve located on top of the filter is opened by the operator to initiate backwash. The trapped air dislodges the filter cake and captured solids in its rush to the air-relief valve. The expended filter aid is then washed to waste. The loss of production of filtered water due to the time that it takes to backwash is minimal, amounting to only 2% according to estimates for operation under combat conditions.²⁶

The section of the van that contains the two diatomaceous-earth filters also includes the filter pumps. The pumps are used to provide water to the filters, as well as to flush the filters after backwashing. Also included are pressure gauges, flow controllers, air-relief valves, precoat tanks, and the necessary pipes and valves.

PERFORMANCE OF DEEP-BED FILTERS OPERATED IN THE DIRECT-FILTRATION MODE

Filtration is a process intended to remove particulates such as bacteria, viruses, algae, protozoan cysts, and clay from water and other liquids. Sand and its derivatives are commonly used as deep-bed filter media, and garnet and coal have been used since the 1960s. The multimedia deep-bed filter used in the 600-gph ROWPU is shown in detail in Fig. 8.

The conventional steps for granular-media filtration include coagulation, flocculation, sedimentation, and filtration, as shown in schemes A and B in Fig. 1. No provision is included in the treatment train of the 600-gph ROWPU for flocculation or sedimentation. This approach represents one form of the process called "direct filtration". Many papers have been published about the proper operation of the flocculation and sedimentation steps for filters operated in the conventional mode, but because the focus of this report is the ROWPU, those papers have been omitted from further consideration herein.

For good performance of a conventional filtration plant, the consensus is that proper coagulation is the most important of the three steps (coagulation, flocculation, and sedimentation) that may precede filtration.²⁹⁻³¹ Incomplete particle destabilization occurs with coagulant doses that are either too high or too low; this permits particles to pass through the filter. An Environmental Protection Agency (EPA) study³² on the removal of Giardia muris cysts and coliform bacteria gives evidence that although some

Table 1. Effect of coagulant dosage and type on the removal of *Giardia muris* cysts and coliform bacteria by direct filtration with preliminary flocculation.^a (20- to 30-min flocculation time, 20°C water temperature, and low-turbidity feed water.)

Coagulant	Coagulant dose (mg/L feedwater)	Filtered- water turbidity (NTU) ^b	Cyst removal (%)
None	--	0.35	59 to 94
Alum	1.8	0.60 to 0.65	94
Alum	1.9	0.77 to 0.79	23
Alum	2.1 to 2.2	0.46 to 0.63	63 to 88
Alum	7	0.32	>95
Alum	9.8	0.26	99.7
Alum + nonionic polymer	11 + 0.01	0.08	99.75

			Coliform removal (%)
None	--	0.54 to 0.72	44 to 62
None	--	0.26 to 0.47	96.4 to 98.1
Alum	30	0.24 to 0.42	98.7 to 98.9
Alum	30	0.22	99.2
Cationic polymer	0.5	0.16 to 0.21	97.7 to 98.7

^a Adapted from Logsdon and Fox.³²

^b NTU = nephelometric turbidity unit.

removal is obtained with even inadequate coagulation, the performance of the filter is much enhanced with properly coagulated water. Evidence of this enhancement is given by the data presented in Table 1.

Because the coagulation step is so important, it behooves the equipment operator to use the best type and optimum dosage of coagulant in order to achieve maximum filter performance. A number of tests have been proposed that might be used to judge the appropriate coagulant dosage and type. These include the jar test, zeta-potential measurements, and particle-size-distribution analysis. The advantages and limitations of these tests will be discussed in detail subsequently.

One technique for monitoring filter performance involves the use of turbidity measurements, and another is by particle-size-distribution analysis of the filter feed and effluent waters. Early filter breakthrough can be detected with continuous or frequent turbidity measurements. Logsdon and Fox³² state that this is particularly important for filters required to remove viruses or *Giardia* cysts. To date particle-size-distribution analysis has not been used much for the control of the filtration process, but turbidity has been almost always measured since the early times of rapid sand filtration.

The impact of backwashing is also noteworthy. Backwashing is necessary when turbidity rises.³² Backwashing should be initiated as soon as the operator notices rising turbidity, even though the turbidity of the effluent is still <1 NTU. In an EPA study to be discussed in a later section,³³ it was found that "a small increase in turbidity can be associated with a dramatic increase in cyst concentration."

When the filter is returned to service after backwashing, poor effluent-water quality may be experienced for a short time. Filtering to waste until the quality of the filtered water improves is a commonly used strategy.³² Harris³⁴ found that when a nonionic polymer was added to the backwash water, low-turbidity filtered water was produced immediately after the filter run began. The nonionic polymer was thought to improve the adsorption of particles.

The seemingly close association of turbidity removal with the removal of microorganisms in deep-bed filtration made it necessary to review direct-filtration papers dealing solely with turbidity. Some of those studies will be covered in detail in the following sections of this report.

DETERMINATION OF BEST TYPE AND OPTIMUM DOSAGE OF COAGULANT

Adin and Rebhun³⁵ injected a cationic polyelectrolyte (Cat-Floc) into a 1/2-in. pipe leading to two 2-1/4-in. i.d. sand-filter columns. The blending between the coagulant and the water containing 20 mg/L of kaolinite clay was achieved by the turbulence created between the jet derived from the coagulant-injection needle and the flow of the water through the pipe and two 90-deg elbows. The two filters consisted of sand columns, 5 and 15 cm deep, with an effective grain size of 0.62 mm. The hydraulic loading was held constant at 5 m/h ($2.0 \text{ gal}/[\text{min} \cdot \text{ft}^2]$). Jar tests were performed simultaneously with the filter studies as shown in Fig. 16. The optimal jar-test coagulant dosage closely matched the dosage giving the best filter performance, but the filter was much more tolerant to off dosages.

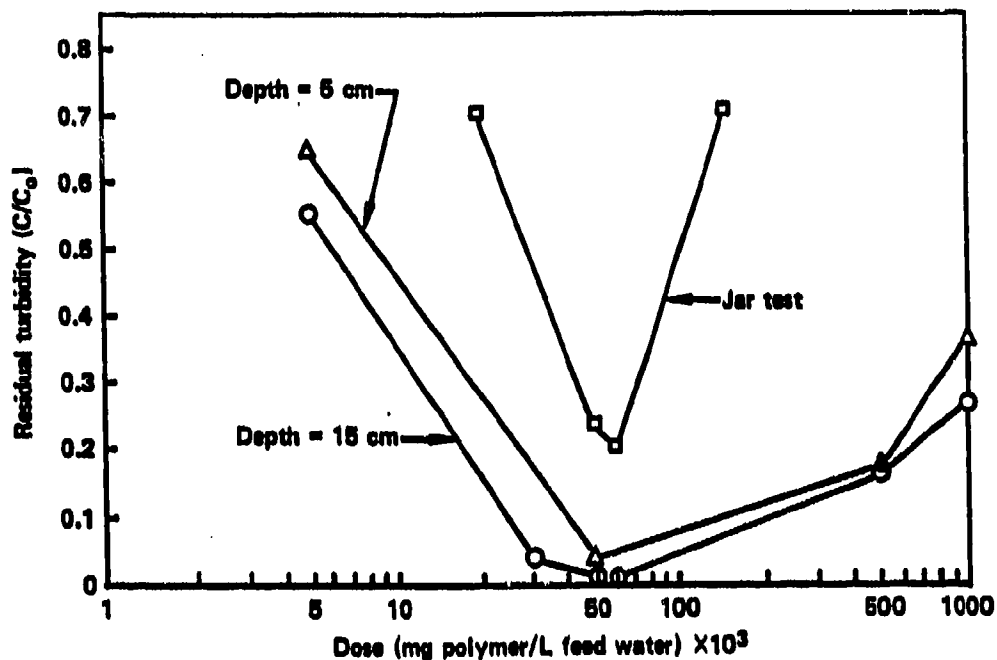


Figure 16. Comparison of jar-test results with the passage of kaolinite turbidity through rapid sand filters, where C/C_0 is the ratio of the turbidity of the treated water to that of the untreated water (kaolinite = 20 mg/L, cationic polymer, filtration rate = 5 m/h). Adapted from Adin and Rebhun.³⁵

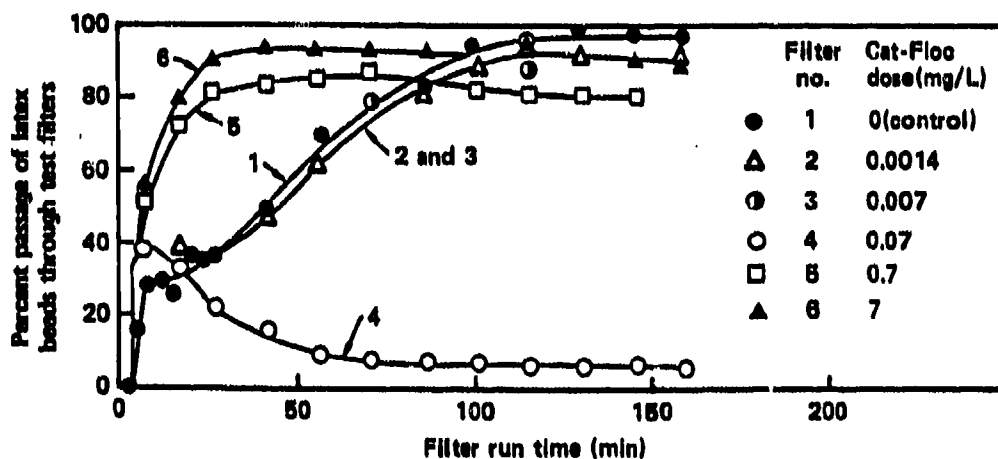


Figure 17. Effect of polyelectrolyte dose on the passage of 0.1- μ m latex beads through a deep-bed filter. (Bead concentration = 9.7 mg/L, filtration rate = 2 gal/[min \cdot ft²].) Adapted from Habibian and O'Melia.³⁶

Habibian and O'Melia³⁶ conducted a study to investigate the role of chemical parameters in direct filtration. Suspensions of different sizes of latex beads were coagulated with various cationic polymers and filtered through six test-filter columns operating under the same conditions but receiving different polymer dosages. No information was given on the type of filter media used or the kind of mixing employed. One filter was operated as a control with no polymer; two were underdosed relative to the results of jar tests; two were overdosed; and one was operated at the optimum jar-test dosage. The filtration rate was kept constant at $2 \text{ gal}/(\text{min} \cdot \text{ft}^2)$, and all filter media were precoated with polymer prior to the start of a filtration run.

The results of the experiments for the $0.1\text{-}\mu\text{m}$ latex particles and the Cat-Floc polymer are shown in Fig. 17. The optimum jar-test coagulant dosage was determined to be 0.07 mg/L . The control and the two test columns receiving gross underdoses of the coagulant (runs 1, 2, and 3 in Fig. 17) gave constant concentrations of the latex particles in the filtered water, as determined by turbidity soon after the start of the filter runs. The passage of the particles through the filter remained constant for a while and then increased rapidly to nearly 100%. The two filters receiving gross overdoses of the coagulant (runs 5 and 6 in Fig. 17), performed poorly almost immediately after the start of the filter runs. At the optimum dose as determined by the jar tests (run 4 in Fig. 17), the passage of the particles through the filter attained a maximum value of approximately 40% soon after the initiation of the filter run, and then decreased to a constant minimal value of less than 10%. Filtration in this run was so effective that the 7.5-ft (of water head) allowable pressure drop across the filter column was reached in less than 3 h of continuous operation.

Jar-test results for the $1.099\text{-}\mu\text{m}$ latex particles using polyethylenimine coagulants with molecular weights ranging from 600 to 100,000, but with almost equal charge densities (as determined by acid-base titrations), indicated that the optimum coagulant dosage was nearly the same for all the polymers regardless of their molecular weights, except for the lowest-molecular-weight polymer that also had a higher charge density. This indicated that charge neutralization plays a significant role in the coagulation of latex particles by polyethylenimine. Subsequent electrophoretic-mobility measurements indicated that the optimum dosage occurred at negative zeta potentials. This finding confirms the effect of charge neutralization, but since optimum dosage did not occur at zero zeta potential (zero mobility), it also indicates that complete charge neutralization is not required for effective coagulation. From these results the investigators concluded that charge neutralization plays a role in coagulation, although it is not the sole mechanism.⁸

As stated previously, Yao's theoretical and experimental studies showed that the size of the suspended particles affects the removal efficiency of the filter markedly. In order to evaluate the validity of this prediction, Habibian and O'Melia³⁶ filtered suspensions of three sizes of latex particles (0.109, 1.099, and 7.6 μm) through three shallow filter beds 0.8 in. deep. The coagulant, PEI-18 (polyethyleneimine), was added continuously to the filter influents. The polymer dosages were 0.176, 0.032 and 0.024 mg/L, respectively. The initial latex-particle concentrations in the the three filter influents were approximately the same (50, 48 and 52 mg/L, respectively). The particle-removal efficiency was greatest for the 7.6- μm particles. It was also quite high for the 0.109 μm particles for which the maximum allowed pressure drop across the filter bed (85 in.) was reached before particle breakthrough. Filtration of the 1.099- μm particles was the least efficient, and breakthrough was observed at a filter pressure drop of 5 in. of water head. The investigators concluded that the trend in particle-removal efficiency as a function of particle size was in qualitative agreement with Yao's transport model.

Stump and Novak³⁷ investigated the performance of various polymers in a process consisting of rapid mechanical mixing, followed by 20 min of flocculation, and then filtration through a multimedia filter (anthracite, sand, and garnet). The filtration rate was 5 gal/(min \cdot ft²). The feed water, a 100-mg/L kaolinite clay suspension, had a turbidity of 80 formazin turbidity units (FTU). The optimum coagulant dosage obtained by the jar tests provided the longest filter runs. However, the jar tests failed to predict which polymer would perform the best in the filter runs. It was concluded that the jar test could not be used to select the polymer, but it could be used to determine the optimal coagulant dosage for a given coagulant.

Stump and Novak³⁷ also concluded that the low-molecular-weight cationic polymers (molecular weight <10,000) gave poor removals, whereas those with molecular weights in excess of 1×10^6 created excessive filter pressure drops. They recommended a polymer molecular weight within the range of 10,000 to 200,000 for direct filtration. They also recommended that the mean velocity gradient, G , in the flash mixer should be increased with the molecular weight of the cationic polyelectrolyte. A range of about 200 to 950 s^{-1} was recommended for the polyelectrolytes deemed useful for water coagulation.

Electrophoretic-mobility measurements (zeta potential) and more recently particle-size-distribution analyses are also used to help ascertain the optimum coagulant dose. According to O'Melia and Stumm,⁷ zeta potential cannot provide an accurate estimate of the forces affecting the particle attachment in water filtration, and consequently its use as a monitoring tool for correct coagulant dose is limited.

Letterman *et al.*³⁸ performed a study to ascertain whether zeta potential could be used to prejudge the performance of the cationic polyelectrolyte Cat-Floc T in the direct filtration of water having a turbidity of 32 FTU derived from a mix of bentonite-kaolinite clays. The coagulant was blended with the feed water through a pipe tee leading into a mechanically stirred flocculator containing four turbine impellers. The mean velocity gradient G was not estimated for the pipe mixer. The mean flocculation period was 2 to 10 min, depending on the feed flow, and the mean velocity gradient could be varied between 0 and 700 s^{-1} in the flocculator. The water was filtered through 3-in. i.d. dual-media filter columns (anthracite and sand). The filter rate was varied from 2.5 to $7.5 \text{ gal}/(\text{min} \cdot \text{ft}^2)$ during the course of the study.

The polyelectrolyte dosage was adjusted in a filter run performed at a filtration rate of $7.5 \text{ gal}/(\text{min} \cdot \text{ft}^2)$ to obtain a minimum filter effluent turbidity. This corresponded to particle zeta potentials in the range of -5 to +12 mV in the suspension leaving the flocculator. The investigators stated that these results were in good agreement with the principal author's previous studies on direct filtration of natural suspensions from Lake Michigan, using cationic polyelectrolytes.³⁸ In these former tests the particle zeta potentials ranging from -4 to +13 mV corresponded to an interval of minimum turbidity in the filtered water. It was concluded that zeta-potential measurements at or near zero indicated the best coagulant dosage.

Yeh and Ghosh⁵ conducted studies with the objective of developing methods to select polymers for direct filtration. They investigated the influence of polymer molecular weight and charge density on filtration efficiency, as well as the effects of mixing energy on polymer-particle interactions, by using zeta-potential measurements, jar tests, colloid titration, and particle-size-distribution analysis. Cationic polymers (molecular weights ranging from 1200 to 5×10^6) were investigated, including Cat-Floc T (molecular weight = 1×10^5). Studies were performed both in batch- and continuous-flow modes. The batch tests consisted of the jar tests and zeta-potential measurements. In the continuous-flow filtration studies a 3.7-L mixing chamber with a variable-speed mixer was used ahead of a 2.54-cm (1-in.) i.d. filter. The filter contained silica sand with an effective size of 1.0 mm and a uniformity coefficient of 1.2, packed to a depth of 15.2 cm.

It was found that the coagulant dosage that gave the minimum residual turbidity in the jar tests also corresponded to a zero zeta potential. The particle-size-distribution analysis conducted in the continuous-flow studies, on the other hand, indicated a substantially higher optimum polymer dose when measured after 3 min of rapid mixing. The filtration runs indicated that the coagulant dose obtained from the

particle-size-distribution analysis, rather than that given by the jar tests, gave the best filter performance. The investigators concluded that particle-size-distribution-analysis was the preferable method to determine the optimum polymer dosage for direct filtration.

Yeh and Ghosh⁵ concluded that low- to medium-molecular-weight cationic polymers (molecular weights from 10,000 to 100,000) perform best in direct filtration, which is in agreement with the results of Letterman *et al.*³⁸ discussed previously. The investigators recommended that rapid mixing should not be continued for prolonged periods of time because it might cause floc breakup, especially when high-molecular-weight polymers are used. They also concluded that for most direct filtration operations, slow flocculation following rapid mixing is not necessary, especially if the suspended-solids concentration in the raw water is 30 mg/L or higher.

Ghosh *et al.*⁹ investigated the relationships between polymer molecular weight, charge density and dosage, mixing conditions and the flocculated particle-size-distributions in batch reactors. Three groups of commercial cationic polyelectrolytes were tested, including the Cat-Floc group. The study results indicated the following: (1) both charge neutralization and bridging play a role in coagulation with polyelectrolytes, (2) the optimum polymer dosage is independent of polymer molecular weight in most cases, and (3) a strong correlation exists between the optimum polymer dosage and its charge density. It was observed that the optimum coagulant dosage decreased as a power function of the number of cationic charges per molecule, and the power was close to unity for the type of suspensions coagulated in their study (silica and bentonite clay).

Ghosh *et al.*⁹ also compared particle-size distribution and zeta potentials subsequent to rapid mixing and flocculation in a mechanically stirred batch reactor. They found that the polymer dosage yielding the largest mean size of the particles corresponded approximately to a zero zeta potential, regardless of how the mean size was computed. These findings tend to support the concept that charge neutralization plays an important role in polyelectrolyte coagulation, as does the applicability of zeta-potential measurements for the determination of the optimum polymer dose. Particle-size-distribution analyses also indicated that a significant amount of coagulation occurred during the first phase of rapid or flash mixing. The optimum mean velocity gradient G was 800 s^{-1} for most of the cationic polyelectrolytes tested, including the Cat-Floc group. Increasing G beyond 800 s^{-1} failed to improve the coagulation rate.

The experimental data of Ghosh *et al.* also indicated that the charge density of the Cat-Floc group of polymers was independent of the pH of the suspension.⁹

GENERAL BACKGROUND PAPERS

Robeck *et al.*³⁹ observed removals of attenuated poliovirus Type I (Mahoney strain) ranging from 1 to 50% when uncoagulated water was filtered through a dual-media filter with filtration rates of 2 to 6 gal/(min · ft²). Properly coagulated water with no in-line flocculation chambers and no settling tank gave rise to 90-99% removals of the virus, with most removals being >98%. Two kinds of raw water were used: (1) a blend of hard ground water with demineralized water and (2) water from the Little Miami River, OH. The raw-water temperatures varied from 17 to 19°C; the pH varied from 8.1 to 7.7, and the alkalinity ranged from 100 to 200 ppm. The feed-water virus concentration was maintained in the region of 10,000 pfu/mL.*

The dual-media filter contained 16 in. of anthracite coal and 8 in. of Muscatine sand, and the raw water was coagulated with 10 ppm of alum when the raw-water turbidity was 10 JTU[†] or less. The alum dose was increased for higher raw-water turbidities (about 40 JTU). These higher turbidities and alum doses tended to shorten the filter runs. Combinations of alum and polyelectrolytes were tested in a few of the runs. One run lasted 52 h with a pressure drop across the filter reaching 7 ft of water head.

From their experiments, Robeck *et al.*³⁹ concluded that (1) an increase in filtered water turbidity of less than 0.5 JTU, indicating a floc breakthrough, was usually accompanied by a breakthrough of virus, (2) a virus penetration of the filter could occur without a turbidity increase, even though the turbidity might be as low as 0.5 JTU, (3) polyelectrolyte doses as low as 0.05 mg/L helped to increase the floc strength and prevent virus breakthrough, and (4) more than 98% of the viruses could be removed in the dual-filter media at filtration rates of 2 to 6 gal/(min · ft²) if a low but well-mixed dose of alum was fed just ahead of the filters.

A task group of the American Water Works Association (AWWA)⁴⁰ collected and analyzed data available at the time (1980) relative to the performance of direct-filtration water-treatment plants. The objectives of the study were the following: (1) to obtain data on direct filtration, (2) to analyze the results and identify problems, (3) to suggest feasible solutions to the problems identified, and (4) to recommend areas for further research and development. Multimedia filters were installed in a few of the plants, but most of the plants studied included just dual-media filters. Turbidity, color, algae types

* pfu = plaque-forming unit.

† JTU = Jackson turbidity unit.

and concentration, and water temperature were judged to be the most important feed-water quality parameters. Filter media, pressure drop, and filtration rate, as well as the mode of operation and type and dosage of coagulants, were considered to be the most important operating parameters. From the results obtained in this study, it was difficult to distinguish trends in the operating parameters that would point to an improvement in the process performance.

Problems identified with the raw-water quality included the following: (1) a color greater than about 30 to 40 Hazen units tended to move through the filter beds; (2) turbidities greater than about 15 FTU were poorly removed; (3) certain types of diatoms tended to clog the filters; (4) coagulation became slow at low temperatures; and (5) coagulant performance could be poor at the elevated pH values associated with algae blooms. Other problems were related to the presence of iron and manganese. The AWWA committee concluded that problems with direct filtration may be encountered with raw waters containing more than 40 Hazen units of color, 5 FTU of turbidity, 2000 asu/mL [(one areal standard unit (asu) equals $400 \mu\text{m}^2$)] of algae, 0.3 mg/L of iron, and 0.05 mg/L of manganese. They also recommended that water-flow rates should be decreased at low temperatures in order to permit the completion of the coagulation process; otherwise, post-flocculation may occur in the filtered water.

The data related to the types and doses of coagulants used in the direct filtration plants surveyed varied widely, with no operational problems readily identified with the single exception of backwashing. It was observed that the use of polyelectrolytes as coagulants caused stickiness in the filter media, which made the cleaning of the filter bed with backwashing difficult. The formation of mudballs on the surface of both the dual- and multimedia filters was also noted.

Trends were not readily apparent in the information collected on flash-mixing and in-line flocculation. Despite these inconclusive results, the Committee recommended that in-line mixing of the coagulants with the water should be favored over mechanical mixing.

The size of the filter media used proved to be a significant parameter. Anthracite media smaller than 0.8 mm decreased the length of the filter runs considerably and were subject to algae binding. Based on this information, the Committee recommended an effective size of 1.1 mm with a low uniformity coefficient for the anthracite layer. The depth of this layer should be in the range of 37.5 to 90 cm (15 to 36 in.).

It was found that the sand layer in sand-anthracite dual-media beds controlled the filtered water quality. The depth of the sand bed should be about 20 to 30 cm (8 to 12 in.), and the effective size of the media of 0.45 mm, commonly used

in practice, appeared adequate. A third layer of garnet sand (effective size of 0.2 to 0.3 mm) was also used in some of the plants surveyed. It appeared that those plants could successfully treat waters containing turbidities up to 500 FTU, and color up to 1000 Hazen units, at the expense of shorter filter runs.

The filtration rates ranged from about 1 to 6 gal/(min · ft²) in the plants surveyed. The AWWA committee concluded that the higher rates could be applied with careful use of mixing energy and coagulant aids, and recommended a filtration rate in the region of 4 to 6 gal/(min · ft²). The only microbiological data considered by the Committee were those reported by Robeck *et al.*³⁹ in 1962; they concluded that waters derived from the direct-filtration process must be disinfected. They also pointed out the increased need for a good water-quality-monitoring program because the direct-filtration process utilizes little detention time for coagulation ahead of the filters.

A review of the advantages and disadvantages of direct filtration was also prepared by Trussell *et al.*⁴¹ They decided that the quantity and physicochemical properties of the particulate matter determined the success or failure of direct-filtration systems. Other important factors considered included bacterial quality, tastes, odors, and color of the raw water. Direct filtration should be viewed with extreme caution when the raw water contains high levels of coliform bacteria because it does not provide as many barriers of protection as conventional filtration systems. Moreover, heavy dosing of powdered activated carbon to remove tastes and odors causes significant decreases in filtered-water output. Other observations made by Trussell and co-workers included the increase in performance resulting from the installation of in-line flocculation, and the significant increase in filter pressure drop caused by a bottom layer of garnet without a compensating increase in filtered-water quality. A very coarse top layer composed of pumice or plastic media was also recommended.

The East Bay Municipal Utility District⁴² (EBMUD) headquartered in Oakland, CA, investigated the replacement of alum as a coagulant with cationic polymers in three direct-filtration water-treatment plants. Six cationic polymers, four of which were polymers of diallyldimethyl ammonium chloride and two of epichlorohydrindimethylamine, were tested. The coagulated water was filtered through dual-media filters (3 in. of 0.9-mm effective size anthracite and 27 in. of 0.5-mm effective-size sand, both layers with a uniformity coefficient of 1.4). The filtration rates utilized ranged from 2.0 to 2.5 gal/(min · ft²) with alum coagulation and from 3.5 to 4.0 gal/(min · ft²) with clay-polymer coagulation in two of the treatment plants, and from

2.8 to 3.3 gal/(min • ft²) with alum coagulation and from 4.0 to 4.5 gal/(min • ft²) with clay-polymer coagulation in the third plant.

It was found that the removals of turbidity achieved with alum and the polyelectrolytes were virtually identical when the raw-water turbidity exceeded about 3.5 nephelometric turbidity units (NTU). The alum performed considerably better than the polyelectrolytes for raw-water turbidities in the range of 2 to 3 NTU. The polyelectrolytes gave acceptable turbidity removals when artificial turbidity (clay) was added to the low-turbidity feed waters. In this case the typical filter-run length increased from 23 h with alum coagulation to 47 h with clay-polymer coagulation.

The EBMUD investigators emphasized the increase in the potential for the unreacted polymer to pass through the filter if the clay dosage was low relative to the polymer dosage. Quantitative data could not be obtained because the polyelectrolyte-concentration detectability limits of the analytical methods used were too high. Nevertheless, those investigators recommended the monitoring of polymer residuals in the treated water for future applications. It was also noted that the coagulative properties of the polyelectrolytes tested tended to change with age (storage). Changes in chlorine demand and the growth of microorganisms were also noted.

High alum residuals in filtered water, inadequate plankton removals, and powdered activated carbon breakthrough were the main operational problems encountered in 1978 in the 2×10^8 -gal/d-capacity Alfred Merritt Smith Water Treatment Facility of the Southern Nevada Water System.⁴³ Raw water derived from Lake Mead was filtered at a constant rate of 5 gal/(min • ft²) through dual-media filters (20-in. depth of 0.6- to 0.7-mm effective size anthracite and 10 in. of 0.45-mm effective size sand). Alum and, when necessary, powdered activated carbon were mixed with the raw water in mechanical flash mixers without in-line flocculation or sedimentation.

Pilot-plant tests demonstrated that the operational problems cited previously could be ascribed to insufficient alum flocculation times. The carryover of alum was reduced significantly, and activated carbon doses as high as 20 mg/L could be used for taste and odor control when the water was preflocculated for a period of 15 to 20 min.⁴³

Additional pilot-plant tests were then performed by a consulting engineer. Both direct filtration with and without flocculation and conventional filtration were investigated, using the filter media installed in the existing plant. A few runs were also made utilizing a larger-grain-size anthracite layer with an effective grain diameter of 0.95 mm and a uniformity coefficient of 1.5. It was demonstrated that the conventional treatment gave the best filter performance, but the improvement over the other schemes did not warrant the additional expense of installing sedimentation basins for this

particular lake water. Direct filtration with 30 min of preliminary flocculation yielded longer filter runs; more consistent performance; better turbidity and plankton removals; more even distribution of pressure drop through the filter bed; elimination of activated-carbon-particle breakthrough at high filtration rates; and less coagulant usage than direct filtration without flocculation. These results confirmed the findings of the preliminary pilot-plant studies.⁴³

The plankton problems merit further discussion. It was found that the species or type of plankton was much more important than the total plankton count. Specifically, relatively large numbers of anabaena and anacystis species of bluegreen algae decreased the filter performance significantly. Finally, the results of these studies demonstrated that a 0.95-mm-effective-size anthracite layer was preferable to the 0.6- to 0.7-mm anthracite used in the plant filters. The filter with the larger-size anthracite gave longer filter runs with turbidity and plankton removals comparable to those of the smaller-anthracite-size filter.

Research reported by the University of Washington and the U.S. EPA³² shows a relationship between the turbidity of the filtrate and the removal of cyst-sized particles (5 to 13 μm). Filtrate-turbidity levels must be consistently lower as desired removals of cyst-sized particles increase. It was found that for removals >99.0%, an overwhelming majority of the filtered water samples (88%) had turbidities less than 0.10 NTU. For removals of 90.1 to 95.0% only about a third of the samples had turbidities of less than 0.10 NTU.

Logsdon *et al.*³³ investigated the removal of cyst models and the cysts of *G. muris* in direct filtration with a dual-media filter (46 cm of anthracite with an effective size of 1.27 mm and 15 cm of sand with an effective size of 0.36 mm). Three sets of experiments were run, each with a different type of coagulant. Alum, or alum plus a cationic or nonionic polymer, was blended with the feed water as it was fed through three in-line static mixers in series. (No coagulant was added to the water in some of the initial test runs.) The solution was then flocculated for about 20 to 30 min in a cascade of CSTR reactors. The filtration rate on the dual-media filter was varied from about 2.7 to 7.4 mm/s [4 to 11 gal/(min \cdot ft²)] during the course of the experiments. The most commonly used filtration rate was 2.7 mm/s [4 gal/(min \cdot ft²)].

The water used in the experiments was obtained from a gravel pit. This water was characterized by low turbidity, and experiments were conducted at a water temperature of about 20°C and a pH of 8.2. The cysts of *G. muris* or cyst models (radioactive beads)

were added continuously to the in-line flash mixers to yield initial concentrations ranging from about 470 to 190,000 cysts per liter. The coagulants, when used, were added in amounts sufficient to maintain a filtered-water turbidity of less than 1 NTU.

The removal of the cysts ranged from 59 to 94% when no coagulant was added to the raw water. The removals increased to 99.5% or more during periods of stable operation, when alum was added in quantities sufficient to yield turbidities of ≤ 0.3 NTU in the filtered water, and the initial feed-water cyst count was $> 10,000/L$. Three out of 20 experimental runs yielded filtered-water cyst concentrations $> 100/L$ at a filtration rate of 2.7 mm/s [$4 \text{ gal}/(\text{min} \cdot \text{ft}^2)$].

It was concluded that "a filter treating water dosed with an adequate amount of coagulant and operated in a manner that prevents filtered-water turbidity increases should remove a very substantial portion of the *Giardia* cysts."³³ It was also pointed out by the investigators that the continuous passage of a small number of cysts through a dual-media filter operated in the direct filtration mode cannot be ruled out.

Some other observations of interest were also made by Logsdon *et al.*³³ Increasing the filtration rate by 50, 100, or 150% in less than 10 s increased the passage of turbidity and cysts through the filter. The simultaneous application of alum and a nonionic polymer helped to mitigate this effect at 20°C , but not at 10°C . Sudden surges in flow rate also dislodged the turbidity and cysts stored in the filter. For example, increasing the filtration rate abruptly from 11 to 27 m/h then back to 11 m/h [4.5 to $11 \text{ gal}/(\text{min} \cdot \text{ft}^2)$, then to $4.5 \text{ gal}/(\text{min} \cdot \text{ft}^2)$] for a period of 2 min increased the filtered-water turbidity about 4-fold and the cyst concentration about 25-fold. Finally, initial filter-ripening periods (allowing equipment to operate for a while to improve performance) lasting about 0.5 h were evidenced in the experiments. The filtered-water cyst concentrations were about 10 to 25 times greater than those during stable operation (immediate performance monitoring) during these initial periods.

Rebhun *et al.*⁴⁴ determined the removal of organic colloids by direct filtration. The study apparatus used (for feeding, dosing, flowmeter, and flow-control arrangements) was similar to that used in an earlier work discussed previously in the section on determination of the best type and optimum dosage of coagulant.³⁵ Two filter columns, one with a 5-cm i.d. and 15-cm media depth, and the other with a 4-cm i.d. and 100-cm media depth, were used. Both columns had the same dual media: A coarse quartz sand with a 1.21-mm effective size and 1.17 uniformity coefficient on top of a medium-grade quartz sand with a 0.62-mm effective size and 1.21 uniformity coefficient. The media porosities were 0.4 and 0.37, respectively.

The feed water contained 10 mg/L of a humic acid dispersion, and the coagulants tested were alum, polyelectrolytes, and alum plus polyelectrolytes. The mean residence time given for coagulation was only 2 to 3 min. It was found that effective filtration could be achieved with a combination of alum and a cationic polymer if the doses of the coagulants were carefully selected. Alum or cationic polymers (Magnafloc R-140 and R-139, Cat-Floc C), added singly, failed to give acceptable results.

McCormick and King⁴⁵ determined the removal of turbidity, color, algae, and total coliform bacteria from various surface waters located in the Commonwealth of Virginia with a direct-filtration pilot plant. The results of this study are of special interest here because the modes of operation, filtration rates, and type of coagulants used were often similar to those used in the 600-gph ROWPU.

Alum and/or cationic polyelectrolytes were blended with the raw water in a mechanical flash mixer. The blended water could then be introduced into a mechanically stirred flocculation basin or bypassed to the filter-pump well. (The flocculation basin was not utilized in most of the experiments.) The water was then pumped to one of the three 9.2-cm-i.d. gravity-filter columns that contained the types of filter media listed in Table 2.

The mean residence times were 3, 28, and < 10 min in the flash mixer, flocculation basin, and filter-pump well, respectively. The mean velocity gradients utilized in the flash mixer were 1290 s^{-1} for alum coagulation and 1650 s^{-1} for polyelectrolyte coagulation. The mean velocity gradient was varied between approximately 20 and 63 s^{-1} in the flocculation basin when the flocc basin was used. The water was usually filtered at a rate of 12.6 m/h [$5 \text{ gal}/(\text{min} \cdot \text{ft}^2)$] and backwashed at a rate of 50.4 m/h [$20 \text{ gal}/(\text{min} \cdot \text{ft}^2)$] for 7 min. No mudball formation was observed. A successful filter run was defined as that in which the filtered-water turbidity was always < 1 NTU for a period of at least 8 h.

The quality of the surface waters tested varied considerably. For example, the raw-water turbidity ranged from a minimum of 1.5 to a maximum of 24 NTU. The observed ranges in the other raw-water quality constituents measured were the following: 0 to 42 APHA* color units, 185 to 20,000 algae clumps/mL (not always determined), 1.5 to 12.5°C water temperature, and 0 to 2300 coliform bacteria/100 mL. The optimal doses of the coagulants ranged from 5 to 40 mg/L for alum, and from 1 to 5 mg/L for Cat-Floc T1. Other polyelectrolytes investigated were Cat-Floc 21, Cat-Floc T, and Magnafloc 572 C. The polyelectrolytes were at times mixed together with the alum in the flash mixer.

* APHA = American Public Health Association.

Table 2. Types of filter media used in the direct-filtration studies of Virginia surface waters.^a

Filter number	Media type	Media depth (cm)	Effective size (mm)	Uniformity coefficient
1	coal	25	1.0 to 1.1	<1.7
	sand	30	0.42 to 0.49	1.3 to 1.5
	garnet	23	0.21 to 0.25	1.6 to 2.1
2	coal	51	1.3	1.35
	sand	25	45	1.4
3	coal	51	1.7	1.1
	sand	25	0.45	1.4

^a From McCormick and King.⁴⁵

Firm conclusions could not be drawn for all of the process variables investigated by McCormick and King,⁴⁵ but the following proved to be readily apparent:

- The raw-water turbidity was 10 NTU in 39 experimental runs. These waters were filtered successfully 80% of the time. The failures were ascribed to premature breakthrough of turbidity (15%) and failure to maintain a constant coagulant dosage (5%).
- The raw-water turbidity exceeded 10 NTU in 14 experimental runs. The water was filtered successfully in only three of those runs, and the results for the three successful runs are summarized in Table 3. Failures were ascribed to premature breakthrough of turbidity or a poor-quality effluent at all times.
- The polyelectrolytes tested commonly performed better than the alum, although it was noted that the alum was superior for color removal. A mix of alum and a cationic polymer worked the best of all. Premature turbidity breakthrough occurred in 43% of all the alum runs, 30% of the polymer runs,

and 28% of the runs in which both were applied to the raw water. It also appeared that the polyelectrolytes would have been superior to alum in terms of the projected length of a filter run.

- Large algae concentrations (range of 7000 to 20,000 algae clumps/mL) tended to clog all of the filters tested. The high pH associated with algae blooms also increased the amount of alum that had to be added to the raw water. This, in turn, resulted in a pressure drop across the filters.
- A filtered-water turbidity of less than 0.10 NTU also gave total coliform bacteria counts below the detectable limits of the analytical method used in the investigation.
- It was determined that the effective size of the anthracite layer used in Filter No. 3, 1.7 mm (see Table 2), was too large. Early breakthrough occurred in most of the runs performed with that filter. The rate of increase of filter-pressure drop was significantly greater in the multimedia bed (Filter No. 1) than the dual-media bed (Filter No. 2) in which the effective size of the anthracite was 1.3 mm. It was concluded that the media contained in Filter No. 2 represented the most effective combination of media sizes and bed depths.
- The effects of other parameters investigated could not be judged from the relatively limited amount of data taken in the study. These included water temperature (which was always rather low, 1.5 to 12.5°C), an increase in filtration rate from 12.6 m/h to 20.16 m/h (5 to 8 gal/[min • ft²]), and direct filtration with and without in-line flocculation. It did appear that preliminary flocculation might have improved the performance of the multimedia filter because the 25 cm (10 in.) of anthracite coal placed in that filter was not sufficient to provide the additional detention time required for good bed flocculation.
- The investigators concluded that the raw water should have a turbidity of less than 10 NTU, a color of less than 15 APHA units, and an algae concentration of less than 1000 algae clumps/mL in order to be treated reliably with direct filtration at a filtration rate of 12.6 m/h [5 gal/(min • ft²)].

Table 3. Details of the successful filter runs with Cat-Floc T1 coagulant for raw-water turbidities exceeding 10 NTU.^a

Average turbidity (NTU)		Filter no. ^b	Mode ^c	Temp (°C)	Coagulant dose (mg/L)
Raw water	Filtered water				
10.4	0.40	3	R	5.7	3.7
16.5	0.45	2	R	7	3.5
12.0	0.9	2	RF	4	5.0

^a Adapted from McCormick and King.⁴⁵

^b See Table 2.

^c R stands for rapid mixing followed by direct filtration and RF stands for rapid mixing and flocculation followed by direct filtration.

Hand *et al.*⁴⁶ conducted a bench-scale study to compare the suitability of direct filtration versus conventional filtration for the upgrading and extension of the pretreatment facilities of the Sweetwater Authority Water Treatment Plant in San Diego, CA. The existing plant operating in the "in-line" filtration mode (see Fig. 1) had experienced short filter runs, and product-water turbidities exceeding the 0.5-NTU turbidity standard established by the State of California Department of Health Services.

The raw-water quality appeared to be good enough to be filtered successfully with the direct-filtration mode. The raw-water turbidity was less than 5.5 NTU 50% of the time, and less than 14 NTU 90% of the time. However, it was decided from the bench-scale batch tests that changing from direct filtration to conventional treatment, including flocculation and sedimentation, would serve to improve the performance of the filtration plant significantly.

Cleasby *et al.*⁴⁷ investigated the ability of a 10-cm-i.d. dual-media filter column (40 cm of 1.54-mm effective-size anthracite with a uniformity coefficient of 1.18, and 30 cm of 0.43-mm effective-size sand with a uniformity coefficient of 1.53) to remove particles, using particle counts, turbidity, total coliform bacteria, and standard plate count as indicators. The influent water was taken from a gravel pit, which normally would have supplied high-quality water, but during the testing period was subject to several unanticipated algal blooms. Water pH was adjusted to 6.8 to 7.8 during the

high-pH periods of algae blooms. Alum or Cat-Floc T was blended with the raw water in static mixers, and no flocculation time was provided other than that occurring in the feed lines. The coagulated water was filtered through the dual-media filter at filtration rates ranging from 6.8 to 13.5 m/h [2.8 to 5.5 gal/(min · ft²)].

The raw-water temperature varied considerably during the period of testing (October 1981 to November 1982) as shown in Table 4. The optimum alum dosage ranged within the relatively narrow limits of 6.1 to 12.3 mg/L for raw-water turbidities varying from about 0.4 to 8 NTU. The optimum Cat-Floc T dosage ranged widely from 0.09 to 0.84 mg/L. The results listed in Table 4 indicate that in general, alum coagulation is superior to that achieved with cationic polyelectrolyte as far as effluent quality is concerned.

Other conclusions of this study were as follows: (1) poorer filtrate is found at the beginning of the run, affirming the importance of filtering to waste during ripening at the start of a run for a period of time, especially where Giardia cysts or 7- to 12- μ m particles are of concern; (2) removal of total coliform bacteria was $\geq 86\%$; (3) water as cold as 2°C did not seem to affect the removal efficiencies; (4) longer filter cycles, but poorer-quality filtrate, were obtained using the cationic polymer; and (5) prechlorination with alum was essential during periods of severe algae blooms (prechlorination with the polyelectrolyte proved ineffective). Finally, Cleasby *et al.*⁴⁷ recommended that the raw-water turbidity should not exceed about 16 NTU with "small" algae populations or 11 NTU with "moderate" algae populations for the cationic polymer to be effective.

600-GPH ROWPU PRETREATMENT UNITS

Small *et al.*¹ conducted a study on the removal of microorganisms by the 600-gph ROWPU pretreatment system without chlorination in 1979-80. River water (Monocacy River, MD) was first coagulated and then filtered through a multimedia pressure filter (Culligan Model MD30 Mixed-Media Filter) similar to the one installed in the current 600-gph ROWPU. The filtered water was then pumped under pressure through cartridge filters. The raw water was coagulated with a cationic polymer (Cat-Floc T) at an average dosage of 5.0 mg/L (4.3 to 5.6 mg/L). Three filtration rates of 6.5, 7.6, and 8.7 gal/(min · ft²) were investigated in nine experimental runs lasting 9 h each. These filtration rates are equivalent to feed-water flows to the ROWPU of 30, 35, and 40 gal/min. The operation of these pieces of equipment was as described in the technical manual for the 600-gph ROWPU.¹⁸

Table 4. Average removal of total coliform bacteria and particles in the 7- to 12- μ m size range for direct dual-media filtration without chlorination.^a (Filtration rates were varied from 6.8 to 13.5 m/h.)

Coagulant	Temp (°C)	Coliform bacteria		Particles (7 to 12 μ m in size)	
		Influent (number/ 100 mL)	Removal after filter ripening (%)	Influent (number/ 100 mL)	Removal after filter ripening (%)
Alum	7 to 14	1300	91	2320	98.8
Cat-Floc T	4 to 5	8200	96.5	1170	96.7
Cat-Floc T	3 to 4	1500	89.7	370	87.0
Alum	2	1600	96	2190	99.0
Cat-Floc T	3	640	89	1620	98.0
Alum	6 to 7	350	91.3	2860	94.0
Alum	17	90	86	13040	99.0
Cat-Floc T	21 to 23	50	86	1350	85.5
Alum	20 to 24	550	89	1640	96.5
Cat-Floc T	23	170	86.5	340	87.5

^a From Cleasby et al.⁴⁷

The cartridge-filter elements had the same nominal size rating as those used in the current 600-gph ROWPU (5 μ m), but they had less surface area. Six instead of eight polypropylene Filterite elements were housed in one pressure vessel.

The ranges in the temperature, pH, turbidity, TDS concentration, and alkalinity of the Monocacy River water are shown in Table 5. The water had a total organic carbon (TOC) content of approximately 5.1 mg/L, and an immediate chlorine demand of about 1.4 mg/L. Cultures of Bacillus globigii spores and poliovirus 1, LSc strain were well mixed with the river water prior to adding the coagulant. The feed-water concentrations ranged from 220 to 15,000 colony-forming units (cfu)/mL for B. globigii, 14 to 8500 cfu/mL for in situ Escherichia coli, 440 to 1720 plaque-forming units (pfu)/mL for poliovirus, 354 to 24,290 cfu/mL for total in situ bacterial counts, and 204 to 11,190 cfu/mL for total in situ enterics.

The average removals of turbidity are shown in Table 6 for various run times up to 9 h. As might be anticipated, most of the turbidity removal took place in the multimedia deep-bed filter, and the removals increased with filter ripening. Table 7 lists the observed removal of the microorganisms averaged over all run times, and Table 8 shows the average removal of the total aerobic bacteria (determined by standard plate count) for the three water flows investigated. Again the results support the contention that most bacteria and viruses are removed in the multimedia filter and almost none in the cartridge filters. The data shown in Table 8 are erratic, making it difficult to judge the effect of feed-water flow on the removal of total aerobic bacteria, except possibly to say that removal may have decreased at the highest feed-water flow tested (40 gal/min). The investigators concluded that a 40-gal/min feed-water flow probably should be avoided, and that operations at 35 gal/min may be acceptable.

Small *et al.*¹ also concluded that the removals of the microorganisms shown in Tables 7 and 8 are not meaningful in terms of providing an effective barrier against the transmission of infectious diseases. The major line of defense against pathogens would have to be disinfection if the RO section of the ROWPU were to be bypassed. They also pointed out that the results of this study cannot be used to predict the removal of amoebic cysts. They did suspect that the cysts would be better removed than the bacteria due to their larger size.

J. B. Duncan⁴⁸ conducted tests on the removal of *B. globigii* spores, *E. coli*, *Saccharomyces cerevisiae* (a yeast) as a cyst simulant for *Entamoeba histolytica*. He made total plate counts and total enteric bacteria (as defined by Small *et al.*¹) with two 5.25-in. i.d. filter columns packed with the multimedia used in the 600-gph ROWPU (see Fig. 8). Soil from Frederick County, MD, was collected, ground, and sifted through 175-mesh screens. The fines were then mixed with Fort Detrick, MD, tap water to yield feed-water turbidity levels of 50 and 120 NTU. A particle-size-distribution analysis indicated that most of the suspended particles had sizes of $< 50 \mu\text{m}$. The suspension pH was then adjusted to 5.5, 7.5, and 9.5 with carbon dioxide or sodium carbonate, and then the water was pumped through the filters at a filtration rate of $6.3 \text{ gal}/(\text{min} \cdot \text{ft}^2)$. The two filter columns were arranged in parallel and the run lasted for 4 h. A filtration rate of $6.3 \text{ gal}/(\text{min} \cdot \text{ft}^2)$ is equivalent to a total ROWPU feed-water flow of 31 gal/min.

The turbid feed water was seeded first with the microorganisms and then a Cat-Floc polyelectrolyte in a pipeline leading to the filters. The polyelectrolyte dosage was not stated in the preliminary report. The flow was then divided and delivered equally to the

Table 5. Raw-water characteristics of Monocacy River.^a

Date	Run time (h)	Turbidity (NTU)	pH	TDS (mg/L)	Alkalinity (mg/L as CaCO ₃)	Temperature (°C)	Plant flow (gal/min)
9/17	0	3.5	7.9	278	120.4	19.4 to 22.3	30
	3	3.5	8.0	275	116.8		
	6	3.7	8.4	270	116.8		
	9	4.0	8.4	258	116.8		
9/18	0	6.0	7.9	262	113.1	20.6 to 22.8	35
	3	5.9	8.2	275	116.8		
	6	5.5	8.4	258	113.1		
	9	5.6	8.4	322	113.1		
9/23	0	4.7	7.8	288	120.4	22.2 to 24.0	40
	3	3.9	7.8	267	120.4		
	6	3.8	8.4	262	113.1		
	9	4.0	8.4	260	116.8		
10/9	0	3.5	7.9	274	153.9	14.4 to 17.7	40
	3	4.2	8.1	286	173.8		
	6	3.8	8.4	267	158.9		
	9	3.8	8.5	260	158.9		
10/10	0	2.4	8.1	282	158.9	14.2 to 14.8	30
	3	2.3	7.9	267	148.9		
	6	2.2	7.8	270	151.4		
	9	2.4	7.8	294	153.9		
10/15	0	4.3	7.8	289	148.9	11.2 to 13.8	35
	3	4.3	7.8	300	158.9		
	6	3.1	8.0	278	158.9		
	9	3.3	8.1	272	156.4		
10/22	0	3.0	7.7	282	171.3	12.7 to 14.8	35
	3	3.1	7.7	305	166.3		
	6	3.0	7.7	285	161.4		
	9	3.1	8.0	286	158.9		
10/23	0	3.2	7.7	309	156.4	10.6 to 12.5	40
	3	2.9	7.5	293	158.9		
	6	2.9	8.0	304	163.8		
	9	3.2	7.8	285	158.9		
10/29	0	7.1	7.6	398	213.5	10.0 to 12.4	30
	3	6.7	7.9	424	213.5		
	6	5.1	8.0	445	228.4		
	9	5.0	8.0	452	248.2		

^a Adapted from Small et al.¹

Table 6. Average removal of turbidity observed for a filtration system similar to that in the 600-gph ROWPU pretreatment section.^a

Elapsed time (h)	Turbidity removal (%)	
	Across multimedia filter	Across system
0	67.3	74.4
3	81.4	84.0
6	83.5	86.4
9	85.9	88.1

^a Adapted from Small *et al.*¹

Table 7. Average removal of microorganisms observed for a filtration system similar to that in the 600-gph ROWPU pretreatment section.^a

Organism	Microorganism removal (%)		Overall
	Across multimedia filter	Across cartridge filters	
<u>B. globigii</u> spores	98	1	98
<u>E. coli</u>	91	3	94
Poliovirus I	72	8	80
Total aerobic bacteria ^b	74	9	83
Total enteric bacteria ^b	84	3	87

^a Adapted from Small *et al.*¹

^b As defined by Small *et al.*¹

Table 8. Average removal of total aerobic bacteria observed for a filtration system similar to that used in the 600-gph ROWPU pretreatment section for various feed-water flows.^a

Feed-water flow (gal/min)	Total aerobic bacteria removal (%) ^b		
	Across multimedia filter	Across cartridge filter	Across system
30	86	3	90
35	45	48	93
40	78	-45	33

^a Adapted from Small *et al.*¹

^b Average of three runs per feed-water flow; across-system value would be sum of across-multimedia and across-cartridge filter values, only if perfect sampling and recovery occurred.

two test-filter columns. Chlorine was added to the feed water entering one of the columns while the other column was used as a control. The concentrations of the microorganisms seeded to the feed water were determined after adding the polyelectrolyte. Only the results of the control studies are discussed herein. (Much more information is required to evaluate the disinfection studies than that which was presented in the preliminary report.)

The initial concentrations in the filter influent of the organisms tested were commonly in the range of thousands of cfu/mL except for *E. coli*, which had arithmetic mean initial counts of 68,000 cfu/100 mL at a pH of 5.5, none detectable at a pH of 7.5, and 1200 cfu/100 mL at a pH of 9.5. The observed removals of the microorganisms are summarized in Table 9. (No information on turbidity removal was given in the preliminary report.) In all cases, removal was inconsequential, as far as providing an effective secondary barrier against the transmission of waterborne diseases. Disinfection (chlorination in this case) is the primary barrier. However, the coagulant dosage may have been less than optimal for the large concentrations of suspended solids contained in the feed water.

Follow-up tests were run by Duncan⁴⁸ using river water obtained from the Monocacy River, MD. The raw water had a turbidity of 19 NTU and a pH of 8.3. Approximately 10^6 cfu/mL of B. globigii spores were added to the raw water. The multimedia filter removed 99.86% of the spores on the average, and the cartridge filter removed 70.79% of the remaining spores. The river-water pH was then decreased to 7.0 with carbon dioxide and the test was repeated. The multimedia filter removed nearly all of the B. globigii spores (initial concentration = 10^5 cfu/mL). Unfortunately, the information made available to our investigators does not state whether the water was prechlorinated or not. In view of the results shown in Table 9 for unchlorinated water, one has to suspect that chlorine may have been used in these follow-up tests.

PERFORMANCE OF CARTRIDGE FILTERS

The current 600-gph ROWPU pretreatment system includes eight Filterite polypropylene cartridge filters, as shown in Fig. 10. These filters have a nominal size rating of 5 μ m. Most bacteria and all viruses are smaller than this size rating and are also smaller than the 3- μ m absolute rating now being considered as a replacement for the 5- μ m cartridge filters. An important contribution to pathogen removal to be made by the cartridge filter could be in the area of cyst removal. Giardia lamblia cysts have a minimum dimension of 7 μ m, and E. histolytica cysts are commonly larger (6 to 18 μ m).

It appears that very little research relevant to the purposes of our study has been performed with cartridge filters. Long⁴⁹ evaluated 17 cartridge filters having various size ratings for removal of a microsphere cyst model (5.7 μ m in diameter). The microspheres were filtered from a solution containing 40,000 to 65,000 microspheres/mL, diluted with tap water. No further information was included in the article regarding pH, temperature, etc. More than 99.99% of the microspheres was removed in 10 of the 17 filters tested. It is interesting to note, however, that filters with size ratings of 1.0, 2.0, and 5.0 μ m did not satisfy the 99.99% removal criteria, whereas some filters with ratings of 2.0, 3.0 and 10.0 μ m did. In addition, two filters rated at the same size, 5 μ m, had widely varying particle removals (99.96 vs 21.4%).

It was not possible to determine from the article whether the filter used in the 600-gph ROWPU was tested. In view of the large discrepancies in the results, however, it is clear that the performance of cartridge filters may be highly variable.

Table 9. Average removal of microorganisms from a turbid water for three pH values by a multimedia filter similar to that used in the 600-gph ROWPU.^a (Filtration rate = 6.3 gal/(min • ft²) and feed-water turbidities of 50 and 120 NTU.)

Organism	Microorganism removal ^b (%)		
	pH = 5.5	pH = 7.5	pH = 9.5
<i>B. globigii</i> spores	81	83	90
<i>E. coli</i>	63	ND ^c	75
<i>S. cerevisiae</i> (6- to 18- μ m elliptic yeast cells)	84	ND ^c	94
Total aerobic bacteria ^d	80	70	87
Total enteric bacteria ^d	82	42	63

^a Adapted from Duncan.⁴⁸

^b Arithmetic averages.

^c None detected in the water supplied to the multimedia filters.

^d As defined by Small *et al.*¹

Carbon-impregnated cartridge-filter elements were tested during the early stages of the development and design of the 600-gph ROWPU.¹⁷ Cartridge-filter elements ranging from 3 to 20 μ m in size rating were tested. It was found that the filter elements with the smaller size ratings gave better-quality effluents, but a trade-off had to be made between filter life and effluent quality. The data showed that a filter element with a size rating of 5 μ m produced a water with a turbidity of <0.5 FTU, and had an average useful life of 72 h. The useful life is apparently designated as the time required to yield a 20 psid¹⁸ or 25 psid¹ pressure drop across a filter element.

Radoski⁵⁰ investigated the removal of diesel fuel from tap water with carbon-containing cartridge filters. It was claimed that the filtered water was free of any objectionable taste or odor at a water temperature of 14 to 19°C when the feed water contained 1 mg/L of the diesel fuel.

PERFORMANCE OF PRECOAT FILTERS OPERATED IN THE DIRECT-FILTRATION MODE

In a very early literature review, Cummins⁵¹ states that size distribution and particle shape of the filter-aid media are very important factors in diatomaceous-earth filtration.

The performance of a diatomaceous-earth filter aid can be improved by coating it with an electropositive coating medium. The filter-aid coating is attained either by mixing the diatomite and coating material prior to application of the filter aid or by filtering water with the coagulant in it through the filter aid after it has been applied. A 1936 patent by Cummins states that a filter aid coated with alum is more effective than an uncoated aid in removing suspended solids from water. Diatomaceous earth coated with alum is less permeable to water than uncoated diatomaceous earth of the same grade, but the coarser grades coated with alum are more permeable than the uncoated finer grades, although each may possess similar capacities for the removal of turbidity, coliform organisms, and color. It was concluded that the use of alum coated filter aid was advantageous due to the reduction in pressure drop.⁵²

The Department of Water and Power of Los Angeles, CA, carried out a study on diatomaceous-earth filtration for the city's water supply in 1951.⁵³ It was found that slimy materials, large concentrations of algae, and close-textured diatoms shortened the filter runs. Turbidity resulting from more than 20 ppm of suspended silt particles, as well as any fine floc reaching the filter, were "troublesome."⁵³ It was also found that dissolved and entrained gases had no appreciable effect on the filter efficiency, provided that sufficient backpressure was maintained to prevent the release or entrainment of gases in the filter.

The openings in the septa used in the Los Angeles study varied from 25 to 250 μm . The septum with the largest openings required a longer time to precoat, but the precoating time was fairly constant for septa with openings finer than 160 μm . The septum with the smallest openings had the largest initial pressure drop, tended to clog rapidly, and was difficult to clean. The clogging in the precoated filter elements was caused by the finer filter-aid particles contained in the precoat, and was more noticeable with the thicker septa. It was concluded that the largest opening capable of retaining the filter aid should be used to minimize pressure drop and clogging.

Microorganism removal in the tests agreed with the previously observed 0 to 96 % removal for bacteria derived from treatment of swimming-pool water, depending on how long into the filter run the sample was taken. The passage of bacteria through the filter increased rapidly as the size of the filter aid increased. For the most economical operating conditions employing the coarse filter aids and thin precoats, there was a tendency for bacterial breakthrough, and this was especially evident at pressure drops across the filter elements > 10 psi.

Oulman *et al.*⁵² conducted a study to determine and evaluate the effects of adding cationic polyelectrolytes to the feed water continuously or during the precoating operation of the diatomaceous-earth filters. The parameters investigated included polymer dose, filter-cake permeability, pH, and removal of turbidity, bacteria, and color. The effects of coating the filter aid with the polyelectrolytes were explained by the fact that the coating increases the contact area between the suspended particles and filter aid, and decreases the probability of desorption of an adsorbed particle. It was demonstrated that filter aid coated with polyelectrolytes provides a more complete removal of turbidity, bacteria, and color colloids with a lower pressure drop than the same filter aid without a polyelectrolyte coat.

A 1965 American Water Works Association (AWWA) Task Group Report¹⁶ stated that many of the municipal diatomaceous-earth filtration systems functioning at the time were inadequate for the following reasons: (1) the equipment for effective precoating, filtering, and backwashing was inadequate, (2) the hydraulic loading rate of 6 to 8 gal/(min • ft²) commonly used in practice was too high for continuous operation at fixed installations, and (3) the equipment was unable to supply filter aid adequately as body feed during the run.

The AWWA report also stated that most of the municipal experience with turbidity removal had been restricted to waters low in turbidity and of good bacteriological quality that required little pretreatment except prechlorination. There was no agreement as to the maximum level of turbidity that could be removed without difficulty, but it was agreed that direct diatomaceous-earth filtration could not be recommended for a grossly or even moderately polluted supply. Appropriate pretreatment (conventional or chemical pretreatment to increase filterability) could widen the application areas for diatomaceous-earth filters. Finally, the AWWA Task Group recommended that the filtration rate be held to 1 gal/(min • ft²) for public water supplies unless available data justify an increase in the rate.

Syrotynski⁵⁴ reviewed the performance of diatomaceous-earth filtration plants in the State of New York. No coagulants were reported to be added to the filter-feed waters. The results of their survey indicated that the total counts of bacteria in the filtered water did not correlate with either initial count or the filtered-water turbidity. In a subsequent report, Syrotynski and Stone⁵⁵ reported that the total microscopic count is decreased about 60 to 90% with direct diatomaceous-earth filtration with no coagulation. Body feed was utilized and the filtration rate was held constant at 1.0 gal/(min • ft²).

Hunter *et al.*⁵⁶ investigated the removal of total coliform bacteria with direct diatomaceous-earth filtration and no in-line coagulation, with and without coated filter aids. The removal of the coliform bacteria increased from 90 to 99.86% as finer grades of diatomaceous earth were tested. The initial feed-water count of the coliform bacteria exceeded 19,000 organisms/100 mL for these runs. Various levels of body feed were utilized with a precoat of 0.1 lb/ft².

Those investigators concluded that: (1) the greater the permeability of the filter aid, the greater the number of coliform organisms that are able to penetrate it; (2) "complete" coliform removal is possible using very fine filter aid for influent coliform concentrations of several thousand organisms per 100 mL; (3) beyond that level, higher influent coliform concentrations give higher effluent concentrations; (4) an increase from 1 to 2 gal/(min · ft²) in the filtration rate did not change the removal of the coliform bacteria significantly; (5) increasing the body-feed filter-aid dosages from 7.5 to 60 ppm did not change the removal of the bacteria significantly; and (6) coated filter aids improved the removal of the bacteria, but the improvement was not sufficient to merit the use of such aids.

Burns *et al.*⁵⁷ coated three different grades of diatomite filter aid (Hyflo Supercel, Celite 545, and Celite 560 manufactured by Johns-Manville Products Corp., Manville, NJ) with a cationic polyelectrolyte (Purifloc 601, manufactured by Dow Chemical Co., Midland, MI). The coating operation consisted of mixing the diatomite for about 5 min in a "dilute solution"⁵⁷ of the polyelectrolyte and pumping the mixture through the filter. The filter cake was then washed with distilled water to remove excess polyelectrolyte. A 1.5-in. diameter flat, horizontal septum (100-mesh stainless-steel wire screen) was used in those experiments. The following three suspensions were filtered: (1) a 1-g/L calcium bentonite clay with particle sizes of 0.8 to 1.0 μm , (2) a 4-g/L Black Hills clay with particle sizes of 0.45 to 0.8 μm , and (3) 30-mg/L Folger's Instant Coffee filtered through a 0.45- μm Millipore filter. The coffee solution was intended to serve as a source of color colloids.

The uncoated diatomaceous-earth filter aids did not remove any of the clayey suspended solids. The removal with coated filter aids increased with the weight of polyelectrolyte added per unit weight of the filter aid. Two different mechanisms were postulated to explain the results of the study. First, the polyelectrolyte coating on the diatomaceous-earth filter aid ensures nearly 100% removal of the suspended clay particles until its charge capacity is exhausted; and second, any subsequent removal is achieved by straining only. The effectiveness of the polyelectrolyte coating deteriorated for pH values in excess of about 6 to 7.

The coated filter aid did not fully eliminate the color produced by the coffee solution under any circumstances. It was concluded that the color was associated at least in part with either nonreactive colloids or dissolved substances. The suspended-solids removal was around 80% with the fully coated filter aids.

A study carried out at the University of Texas⁵⁸ in 1974 reports on the removal of an E. coli T2 bacteriophage by direct diatomaceous-earth filtration. The system used did not include in-line flocculation, and the filter aids were coated with a cationic polyelectrolyte. Filter aids were Hyflo, Hyflo B, Hyflo D, and Celite 560 (manufactured by Johns-Manville Products Corp.). Coatings were Purifloc C-31 (manufactured by Dow Chemical Co.), aluminum and ferric salt hydrates. The experiments were performed with a 0.15-lb/ft² precoat, 50-mg/L body feed, and a 1 gal/(min · ft²) filtration rate. The bacteriophage was added to dechlorinated tap water in amounts sufficient to give a feed water concentration of 1700 pfu/L.

From a series of 2-h runs two filter-aid configurations were selected for additional study: (1) Hyflo filter aid with 0.07 mg/L of polyelectrolyte, and (2) Hyflo D alone (no polyelectrolyte). Two 12-h runs were made. No observable breakthrough occurred after 12 h with the pretreated Hyflo, though breakthrough occurred after 2 h with Hyflo D alone. It was concluded that a good removal of viruses (>99%) could be achieved only with a polyelectrolyte coagulant plus an adequate precoat with certain of the tested aids. Testing was also done to affirm that the polyelectrolyte had no viricidal effect on T2 phage after 4 h at a polyelectrolyte concentration of 0.081 mg/L.

A second stage of testing⁵⁹ at the University of Texas was conducted with procedures identical to those described previously for the T2 phage study. In this case poliovirus, Mahoney Type I was added to tap water; some additional test runs with T2 phage are reported as well. A series of 2-h runs was made. With coated filter aids and polyelectrolyte pretreatment >98 % removal of virus was obtained. The uncoated filter aid, however, gave only 62% removal of poliovirus after 2 h, as opposed to 90% removal of phage T2 after the same period of time.

Two 12-h runs were made with Hyflo filter aid and polyelectrolyte. After 12 h of continuous operation, there was no significant breakthrough of poliovirus.

Two 4-h runs were made with two filter aids to investigate the breakthrough phenomenon. One of the filter aids was coated, the other one uncoated. After 4 h, removal of poliovirus had dropped to 90% for the uncoated filter aid and to 98% for the coated filter aid.

Finally, a series of 2-h runs using T2 phage with three kinds of filter aid at flow rates of 1 and 2 gal/(min · ft²) and pH values of 6.7 and 9.5 were performed. From the results obtained, it was concluded that filter-aid grade and flow rate did not affect T2 phage removal. However, pH did affect removal, with >99.0% at pH 9.5 and 92.3% at pH 6.7 for one filter aid.

It was concluded that >98 % removal of phage T2 and poliovirus can be obtained when a coagulant is added to the filter feed water. Filtration rate, body-feed rate, and filter-aid grade did not appear to affect the removal of the viruses significantly. Surprisingly, it was found that "the same virus removals were obtained either with or without body feed;" hence the body-feed rate was set to maintain cake porosity.

Amirhor and Engelbrecht⁶⁰ investigated the removal of bacteriophage MS2 using direct diatomaceous-earth filtration with Celite 560 (manufactured by Johns-Manville Products Corp.) without body feed. A 0.5-in. thick precoat of diatomaceous earth was applied to the filter, and filtration took place at a filtration rate of 1 gal/(min · ft²). The filter aid was coated with a cationic polymer, Purifloc C-31 (manufactured by Dow Chemical Co.), at quantities equivalent to 0.2 and 0.4 mg of polyelectrolyte per gram of diatomaceous-earth filter aid. The virus was seeded to a distilled-deionized water buffered to pH levels of 6, 7, and 8.

Virtually no virus was removed by the uncoated diatomaceous-earth filter aid as shown in Fig. 18. The coated filter aid gave about 90% removal or better for a run time of 7 h and a pH of 6.0. The results of other tests not given herein demonstrated that the removal of the virus decreased with increasing pH, and breakthrough occurred when the absorptive capacity of the polyelectrolyte was exhausted. A number of experiments were also conducted with an uncoated filter aid and the polyelectrolyte added to the filter feed water. The results demonstrated that the dose of a coagulant must be tailored to the character of the feed water in direct filtration. The lowest dose of polyelectrolyte used in this study (0.25 mg/L) gave the best removal of the virus for the operating conditions used.

Recent studies by Lange *et al.*⁶¹ demonstrated a decrease in the removal of total-colliform bacteria with an increase in the filtration rate. The authors performed the studies on low-turbidity water (4.5 to 5.4 NTU) at filtration rates of 1, 2, and 4 gal/(min · ft²). Unlike the results reported by Hunter *et al.*,⁵⁶ the removal of both total colliform bacteria and standard plate count bacteria increased significantly when the diatomaceous earth was coated with alum. For example, the range in colliform bacteria removal increased from about 30 to 70% without alum coating to about 96 to 99.9% with coating. The authors also concluded that the most important factor in removal of

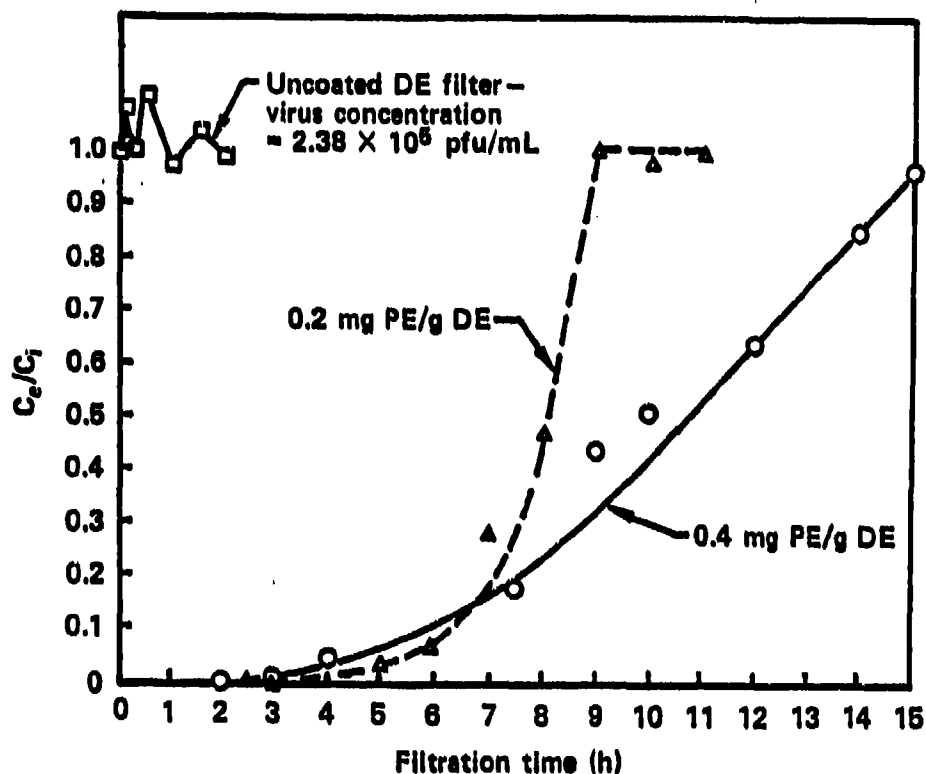


Figure 18. Removal of MS2 bacteriophage by uncoated and polyelectrolyte (PE) coated diatomaceous-earth (DE) filter aid. [pH = 6.0; virus concentration = 4×10^8 pfu/mL; filtration rate = 1 (gal/min \cdot ft²)]. Adapted from Amirhor and Engelbrecht.⁶⁰

bacteria is the grade of the diatomaceous earth. A coarse grade of diatomite gave a 28% removal of coliform bacteria and a 38% removal of standard plate count bacteria, whereas a fine grade of diatomite gave a 99.9% removal of the coliforms and a 99.8% removal of the standard plate-count bacteria.

The cysts of *E. histolytica* and *G. lamblia* are similar in size and surface electrical charge. They are dissimilar in that the pathogenicity of *E. histolytica* has long been known, whereas only recently has the pathogenicity of *G. lamblia* been recognized. Since the mid-70's, research has been conducted in removal and inactivation techniques for *G. lamblia*. Both *G. lamblia* and *E. histolytica* are protozoans that are pathogenic to humans. They are similar in size, the cysts of *G. lamblia* being ovoid in shape, 14 to 16 μ m long and 6 to 12 μ m wide. *E. histolytica* has a spherical cyst form 10 to 15 μ m in diameter. They are also similar in symptoms of disease, i.e., both cause diarrhea. Of

concern to the mobile field Army, the debilitating effects of this condition could render military personnel incapable of action. Because water supply has been incriminated for carriage of both protozoan cysts, the Army is concerned about removal of cysts from its water supply.

According to an early paper by Kominek,⁶² diatomaceous-earth filters are effective in the removal of chlorine-resistant organisms, such as cysts, as well as suspended solids. Kominek hypothesized that diatomaceous earth forms a porous cake with exceedingly fine openings, thereby providing excellent filtration without the refinement in pretreatment technique required for rapid sand filtration.

Leading investigators of diatomaceous-earth filtration for drinking-water treatment were with the U.S. Army during World War II.⁶³ The data contained in an Army report⁶⁴ of July 1944 resulted from the combined efforts of the Office of the Surgeon General (OTSG) and the National Institutes of Health. The experiments are described in the Army publication and were summarized recently by Logsdon *et al.*³³ The intent of those studies was to determine the removal of the cysts of E. histolytica with diatomaceous-earth filtration. Several diatomaceous-earth filtering systems were tested, from small batch systems (4-L volume) to large continuous-flow systems (75 L/min). The precoating water was contaminated in the only run out of a total of 13 where more than one cyst was recovered from the filtered water. It was concluded by both the Army and Logsdon that virtually all cysts of E. histolytica can be removed with direct diatomaceous-earth filtration.

Jones and Brady⁶⁵ studied the removal of Schistosoma mansoni cercariae by filtration through diatomaceous earth in a small model filter. A precoat of 0.15 lb/ft² was used without body feed, and either tap or raw river water was used in the experimental runs. The removal of the cercariae was investigated in nine runs. Varying filtration rates [0.3 to 11.1 gal/(min • ft²)] and applied pressures (0 to 17 psi) were used, as well as three types of diatomaceous-earth filter aids (Sorbo-Cel 503, Speedplus, and 4200+kaolin). Referring to the filtered water quality, the authors state "...there were no cercariae recovered in any of the samples examined."⁶⁵

Baumann and Babbitt⁶⁶ also examined the removal of the cysts of E. histolytica with porous filter septa both with and without filter aid. They were looking for a septum that would remove cysts without filter aid, on the hypothesis that application of the filter aid is the most likely procedure for error. One of the more interesting conclusions made in that report is that "a septum that will effect a removal of roughly 75 to 80% of the applied bacteria will remove also 100% of the applied cysts."⁶⁶ They also concluded that septa with a mean pore size of 18.6 μ m or less will remove all of the cysts.

Logsdon and several associates⁶⁷ and DeWalle *et al.*⁶⁸ found diatomaceous-earth filtration to be effective in removing *G. lamblia* cysts, *G. muris* cysts, and 9- μ m radioactive beads that served as models of *G. lamblia*.

The Drinking Water Research Division of the Environmental Protection Agency (EPA) conducted a study in 1981 on the removal of *Giardia* cysts and cyst models from drinking-water supplies by alternative filtration methods.³³ Radioactive microspheres 9 μ m in diameter were used as *Giardia* cyst models in the first phase of the diatomaceous-earth filtration study. Those spheres are very similar to *Giardia* cysts in size and are easily traced. Logsdon *et al.*⁶⁷ pointed out that data procured from the microsphere studies gave conservative results because in some of their corroborative runs better removals were obtained with *G. lamblia* than with the microspheres. *G. muris* cysts, which are similar in size, shape, and surface electrical charge to *G. lamblia* cysts, were also used later on in the diatomaceous-earth filtration studies because it proved difficult to obtain viable *G. lamblia* cysts on a continuous basis.

Low-turbidity water was obtained from a local gravel pit on the premise that it closely resembled the mountain streams through which giardiasis is commonly spread. The diatomaceous-earth test filter had an area of 0.1 m² (1 ft²) and was operated as a pressure filter with a slurry feeder for body feed. The hydraulic loading rates investigated were 2.4 and 3.5 m/h [1.0 and 1.4 gal/(min \cdot ft²)], and the body-feed-to-turbidity (mg/L to NTU) ratios ranged from 2:1 to 35:1. The entire effluent from the test filter was filtered through 5- μ m membrane sampling filters to determine the removals of the cysts and cyst simulants.

The microspheres were dosed on a continuous basis, and the filter was operated for periods ranging from 2 to 27 h, with a typical run lasting from 6 to 8 h. The *G. muris* cysts were dosed in one slug of 20×10^6 to 40×10^6 cysts, just ahead of the filter-pressure-containment vessel. Filtration was continued until at least 99% of the cysts could be collected on or pass through the filter.³³ After the run the membrane filter was washed and the retained cysts were concentrated and counted.

The results of the radioactive microsphere tests indicated that in most cases more than 99.9% of the microspheres were removed by the diatomaceous-earth filter. The removal of the cysts appeared to be unrelated to the reduction in turbidity.³³ The passage of turbidity at a time in the run when cysts do not pass is attributed to the difference in the sizes of the several kinds of particles. Cysts have a smallest dimension of about 7 μ m; clays and bacteria can be as small as 1 μ m, and thus would be capable of passing through the filter-cake pores, while the cysts would be strained out.

The microsphere-removal efficiencies were found to be related to certain operating conditions. The removals increased with the application of the precoat up to 1.0 kg/m^2 . Additional precoat did not improve performance. The removal consistently equaled or exceeded 99.9% with a precoat of 1.0 kg/m^2 and body feed. Finally, the test results also indicated that the removal capability of the diatomaceous-earth filter usually improved during a filter run. This was caused by the increase in cake depth resulting from the collection of the body feed and suspended solids.³³

The G. muris cyst studies gave good removal at both the 2.4 and 3.5 m/h [1.0 and $1.4 \text{ gal}/(\text{min} \cdot \text{ft}^2)$] filtration rates. Removal was greater than 99.8% with the exception of one run at 99.36%. That particular run was also distinguished by an above-normal amount of diatomite in the filter effluent. The results of this test series also confirmed the finding given previously that cyst removal does not correlate with turbidity removal. It was concluded that diatomaceous earth filtration with body feed and a precoat of 1.0 kg/m^2 removes Giardia cysts effectively and economically as long as the filters are operated and maintained properly, and as long as the filtration rate does not exceed that used in the study [3.5 m/h or $1.4 \text{ gal}/(\text{min} \cdot \text{ft}^2)$].

DeWalle et al.⁶⁸ added Giardia cysts to unfiltered Seattle tap water with a turbidity in the range of 0.6 to 0.9 NTU. The seeded water was not coagulated or disinfected. The ranges in precoat and body feed investigated were 0.5 to 1.2 kg/m^2 and 10 to 40 mg/L , respectively. The Giardia cysts were added as a slug to the filter influent (3.0×10^9 cysts in 10 s). Removal ranged from 99.03 to $>99.87\%$ in 12 separate determinations. The best removal was obtained with the following operating conditions: a precoat of 1.0 kg/m^2 , a body feed of 20 mg/L , an hydraulic loading rate of 3.8 L/min [$0.09 \text{ gal}/(\text{min} \cdot \text{ft}^2)$] and a water pH of 6.7. The removal of the cysts increased as the bed matured during the course of a filter run.

Lange et al.⁶¹ reported Giardia cyst removals of 99.9% for seven grades of diatomaceous-earth filter aids subjected to filtration rates of 2.44 to 9.76 m/h [1 to $4 \text{ gal}/(\text{min} \cdot \text{ft}^2)$] in the water-temperature range of 5 to 19°C . Low-turbidity waters, approximately 5 NTU, were used in the testing.

PERFORMANCE OF THE MWPU (ERDLATOR)

Black and Spaulding⁶⁹ conducted research on the then new Army diatomaceous-earth filtration technique. Half of their experimental runs were made with just filtration, and the other half included coagulation with alum and sedimentation prior to filtration. The concentrations of E. coli were determined with the multiple-tube dilution technique.

The untreated water when filtered "seldom produced negative tests for E. coli in all five tubes even when filtered turbidity was at a minimum." Better results were obtained with the coagulated and settled water. Measurable turbidity (although fairly low) was found in most filtrates obtained from the untreated water.

Special field studies were conducted in the 1950's to assess the performance of the MWPU under closely controlled conditions.²⁸ Table 10 shows results of one series of biological testing on the prototype MWPU. The coagulation process alone provided good reductions of bacteria. Of the six runs made without the addition of chlorine, fecal coliform bacteria were detected in the filtered water of only one of the runs.

Three nonpathogenic organisms (Serratia marcescens, Bacillus subtilis var. niger, and T3 coliphage) were used in another series of MWPU tests. "Very substantial"⁷⁰ quantities of S. marcescens and T3 coliphage were removed by the MWPU without disinfection. For example, an average of 99.6% T3 coliphage was removed by the ERDLATOR, followed by diatomaceous-earth filtration.²²

Bacterial counts showed removals in the ERDLATOR (the clarifier) of 81 to 92% in yet another series of tests when contaminated water with 490 to 33,000 bacteria/100 mL was treated.²⁶ The test water was Potomac River water and standard additions of FeCl_3 and pulverized limestone were used without prechlorination. The turbidities ranged from 25 to 150 ppm in the raw water, and from less than 1 to 3 ppm in the filtered water.

Testing was performed by the National Institutes of Health²⁶ on cysts of E. histolytica at a concentration of 5500 cysts/gal. Cysts were recovered in the ERDLATOR (the clarifier) effluent, ranging from 0 to 8 cysts/gal.

B. subtilis was used as the test organism to assess the MWPU's ability to remove bacterial spores in cold water (35 to 36°F). Table 11 shows the results obtained without chlorination. As the floc bed matured from the beginning of the run through the sixth hour, the removal of spores by coagulation alone increased from 95.45 to 97.36%. The performance of the filter improved substantially when 20 ppm of diatomite body feed was added to the filter influent after 3 h of operation. Spore removal increased from about 86% without body feed to an average of 98.86% with body feed. The overall decrease in the bacterial spores was from about 10^3 - to 10^4 -fold for the entire unit during the time when body feed was added to the filter.

Lindsten and Schmitt⁷¹ conducted a series of tests in 1967 on the performance of a "standard 3000-gal/h, ERDLATOR-type...water-purification unit." The tests were performed to allow comparison of expanded perlite with diatomaceous earth for use in Army filters.

Table 10. Observed removal of total bacteria and fecal coliform bacteria by the MWPU without chlorination in 1952.^a (Raw-water source: Potomac River Water, temperature = 56 to 88°F, turbidity = 28 to 110 ppm during the testing period.^b)

Date	Sample identity	Total bacteria count (number/mL)	Fecal coliform bacteria (MPN/100 mL)
23 May	feed water	1050	4900
	ERDLATOR effluent	6	ND ^c
29 May	feed water	18	610
	ERDLATOR effluent	ND ^c	ND ^c
20 June	feed water	29	5400
	ERDLATOR effluent	ND ^c	ND ^c
	filtered water	ND ^c	ND ^c
1 July	feed water	1300	7900
	ERDLATOR effluent	2	13
	filtered water	ND ^c	ND ^c
10 July	feed water	1030	4900
	ERDLATOR effluent	5	49
	filtered water	1	1.8
7 July	feed water	160	1100
	ERDLATOR effluent	3	46

^a Adapted from Ruiz and Schmitt.²³

^b No further information is available "...the Potomac River is subject to wide variations in quality, typical of surface sources draining densely populated areas."²³ Also, the reporting of turbidity in ppm is as shown in the original report.

^c ND = below the detectability limit of the analytical method used.

The removal of turbidity and total-coliform bacteria was determined for several grades of diatomite and one grade of perlite. The tests were performed daily for a total of 50 d, and the individual test runs lasted 6 to 8 h on each day. The filtration rate was held constant at 25 gal/min per filter or 2.5 gal/(min • ft²). The Potomac River water used as the water source in the tests did not have to be fortified with either turbidity or coliform bacteria. The general ranges in two of the quality characteristics (turbidity and total-coliform organisms) of the raw water are given in Table 12.

The raw water was coagulated but not chlorinated in the ERDLATOR in most of the test runs, but a few tests were made without the addition of any conditioning chemical. The average daily results are shown in Table 12 for the particular test conditions of

Table 11. Observed concentration of the spores of *B. subtilis* var. *niger* in the ERDLATOR floc and effluent, and the filtered-water effluent of the MWPU.^a (Raw-water source: pond water, temperature = 35 to 36°F, pH 7.2 to 7.6, filtration rate = 2.5 gal/(min • ft²), FeCl₃ dose = 49 ppm, limestone dose = 227 ppm, body feed = 20 ppm, feed concentration of spores = 1.8×10^5 /mL on a continuous basis, no chlorination.)

Time (hours of operation)	ERDLATOR effluent (number of organisms/mL)	ERDLATOR floc (10 ⁶ organisms/mL)	Filtered water (number of organisms/mL)
1.5	--	2.75	-- ^b
2.0	--	4.6	-- ^b
2.5	--	5.6	-- ^b
3.0	6000	6.7	17
4.0	4600	7	170
5.0	3200	7	2
6.0	3700	8	11

^a Adapted from Pruett and Lindsten.⁷⁰

^b Body feed not added.

diatomite precoat (0.10 lb/ft²) and body feed (40 to 43 ppm) only and coagulation without chlorination. The results were obtained with three different grades of diatomite, but this grade variation appeared to be insignificant. The dosages of FeCl₃ and limestone listed in Table 12 were obtained by dividing the mass rate of addition of the chemical to the ERDLATOR by the mass flow of the water through the ERDLATOR.

Troubles with the MWPU were encountered on test days 46 and 47. The residual turbidity in the filtered water was considerable and the observed removal of the coliform bacteria was relatively poor. The presence of algae was noted on one of those days. Excluding days 46 and 47, the arithmetic mean removal of turbidity was about 72% in the ERDLATOR, and greater than 99% in the filters. The overall reduction in turbidity was about 500-fold when taken across the entire treatment train. The corresponding values for the total coliform bacteria were about 86% for the ERDLATOR, more than 99% for the filters, and 300-fold for the entire system.

No conditioning chemicals were added to the ERDLATOR on days 51 through 53, and the raw water was seeded with the cysts of *Naegleria gruberi*, a nonpathogenic cyst simulant for *E. histolytica*. The filtered water was not analyzed for *N. gruberi* cysts in one of the three runs, but no cysts were recovered in the remaining two runs for which the

Table 12. Average daily removal of turbidity and total coliform bacteria from Potomac River water in 1967 with the standard 3000-gph MWPU.^a (pH = 7.7 to 8.2, alkalinity = 43 to 84 mg/L as CaCO₃, temperature = 59 to 79°F, filtration rate = 2.5 gal/min • ft², no chlorination, diatomite precoat = 0.10 lb/ft², and body feed = 40 to 43 ppm.)

Day	Doses of conditioning chemicals		Turbidity (NTU)			Total coliforms (number/mL)		
	FeCl ₃ (ppm)	CaCO ₃ (ppm)	Raw water	ERDLATOR effluent	Filter effluent	Raw water	ERDLATOR effluent	Filter effluent
1	25	80	47	14	0.2	575	62	1
2	28	80	50	11	0.1	1150	69	1
3	28	80	46	12	0	1000	104	2
6	43	80	54	34	0.2	1175	164	1
7	41	83	59	17	0	1925	165	5
8	43	86	52	16	0	10700	1070	67
46	22	60	51	NR ^c	4	600	NR ^c	43
47 ^b	73	167	46	11	2	325	44	58
48	40	178	47	7	0	390	33	10
11	44	102	59	19	0.1	6525	370	1
12	32	102	47	12	0	5500	350	1
13	30	107	49	8	0	5625	227	2
16	23	112	44	13	0.2	2275	181	1
17	21	110	48	10	0.1	2425	184	3
18	21	84	52	10	0.2	1900	177	4
21	34	80	46	12	0	1000	83	0

^a Adapted from Lindsten and Schmitt.⁷¹

^b Algae present.

^c NR = not reported.

input concentrations were 3200 and 20 cysts per gallon. The Potomac River water had a turbidity of 20 and 6 NTU on those two days. The temperature was not reported. The diatomite precoat was 0.10 lb/ft² and the body feed was 39 to 40 ppm. It was concluded that the cysts of *N. gruberi* could be effectively removed from the water by sedimentation, and subsequent filtration with body feed through the precoated filters at a filtration rate of 2.5 gal/(min • ft²).

The MWPU was also tested under closely controlled conditions in isolated, restricted military locations where full-scale "live-agent" tests were possible²⁸—that is, where the actual chemical or nuclear warfare agent was used rather than a simulant. The results are summarized briefly as follows for the nuclear and chemical warfare agents.

NUCLEAR WARFARE AGENTS

The results of tests using nuclear warfare agents were reported by Lindsten *et al.*⁷².

- The ERDLATOR in combination with the coagulant ferric chloride and the limestone water conditioner removed 80 to 86% of 2-month-old fission products from water.

- The small amount of radioactive floc particles, which was carried over from the coagulation step, was removed by the diatomaceous-earth filters.

- Conventional treatment in the MWPU followed by post-treatment with mixed-bed ion-exchange resin removed an average of 99.93% of the 2-month-old fission products from the test water during the period when the bed was operating at peak efficiency (5.2 h into the run). As the exhaustion point for the ion-exchange resin neared, the bed became less effective. The capacity of the ion-exchange bed was calculated to be 1560 gal/ft³ when used on contaminated water from White Oak Creek.

- Ion exchange was found to be a significant auxiliary processing step for removing radioactive materials from water. It was recommended that investigation of the ion-exchange process be continued.

- The ability of coagulation to treat water containing radioactive substances is influenced by two factors: (1) if the substance to be treated is present as discrete particles, it should be completely removed, and (2) if the substance to be treated is dissolved in water, then it may be poorly removed (13.3% of strontium-90 and 2.4% of soluble cesium-137); however, if the substance is adsorbed on surfaces, it may be removed in the same manner as was soluble yttrium (96.7%), i.e., by coagulation and filtration.

CHEMICAL WARFARE AGENT GB

The effectiveness of various water treatments for the removal of the nerve gas GB were investigated in 1955.²⁸ It was concluded that coagulation and filtration alone did not effectively remove GB from water. Two pretreatments were required ahead of the MWPU. These pretreatment processes were (1) inactivation of GB at moderate or warm temperatures by alkali hydrolysis (recommended dose was 1 lb of $\text{Ca}(\text{OH})_2$ per 1000 gal of water), and (2) superchlorination, i.e., 100 ppm of chlorine, followed by dechlorination, for cold waters. The recommended doses for achieving 100 ppm of chlorine and subsequent dechlorination were 1.2 lb of calcium hypochlorite per 1000 gal of water for oxidation of the GB and 5 lb of powdered activated carbon per 1000 gal for dechlorination, respectively.

The water after treatment for the chemical warfare agent GB was then purified by the MWPU and was found to be potable and palatable.

DISINFECTION

According to Laubusch,⁷³ Theobald Smith illustrated the relationship among the factors that determine whether disease will be present in susceptible individuals that come into contact with pathogenic organisms with the following expression:

$$D = NV/R, \quad (13)$$

where,

- D = the probability of disease,
- N = the number of organisms,
- V = the virulence of the organisms, and
- R = the resistance of the host organism.

Laubusch⁷³ also mentions that even though all of the elements of Eq. 13 cannot be measured, the expression is still applicable to the consequences of effective water disinfection because disinfection will reduce the values of N and V substantially, possibly even to zero. Generally, however, effective water-disinfection processes are not necessarily designed to achieve the complete destruction of all living organisms (i.e., sterilization), which is more essential in the practice of medicine in order to prevent secondary infections.

Classically, disinfection was introduced to destroy or inactivate the pathogenic organisms, most particularly bacteria, in water that are of intestinal origin.⁷³ However, a variety of disease-producing viruses, helminths, and protozoa, in addition to bacteria, may be present in water and merit attention with regard to the effective disinfection of water.^{73,74} In fact, in seventh volume of Drinking Water and Health⁷⁴ the National Research Council reports that in recent years viruses and protozoan cysts, which incidentally are generally more resistant to disinfection than disease-producing bacteria, are probably responsible for most outbreaks of waterborne disease. Furthermore, microorganisms such as Legionella spp., non-tubercular mycobacteria, and free-living amoeba, which are not of intestinal origin and occur naturally, have also been responsible for outbreaks of waterborne-diseases.⁷⁵

The significance of water as a vehicle for disease transmission is emphasized by the fact that outbreaks of waterborne diseases still occur today, even in countries such as the United States where disinfection is a routine practice.^{74,75} Sobsey⁷⁵ even suggests that many such outbreaks go unreported as a consequence of difficulties related to isolating and identifying causative agents. The National Research Council⁷⁴ cites Akin et al.⁷⁶ as stating that waterborne-disease outbreaks are typically associated with the " ... continuing problems involving consumption of untreated water, errors of insufficient or interrupted disinfection, failures to maintain adequate levels of residual disinfectant in potable water distribution systems, and/or breaches in the systems."

In this section of this volume, we describe the three specific water-disinfection methods likely to be available today for field use by military personnel (more generalized processes, such as filtration, have already been discussed). The three methods of disinfection to be described fall into two categories—physical and chemical treatment. Heating the water falls into the first category and adding iodine (as globaline, which contains tetraglycine hydroperiodide) or adding chlorine falls into the second category.

The method selected for disinfection generally will depend on the quantity of water to be treated (e.g., a quart of water [960 mL] in a canteen for use by a single individual, or multiple gallons of water for use by a large number of individuals) and/or the availability of a treatment process. For example, boiling water in the field is impractical on a routine or large-scale basis⁷³; however, under emergency conditions, such as in the absence of treatment chemicals, it may be appropriate and effective. Furthermore, the amount of treatment necessary is a function of both the resistivity of the organism(s) being treated (i.e., viruses and protozoan cysts tend to be more resistant to disinfection than bacteria⁷⁴), and the physical and chemical character of the water (e.g., temperature, pH, suspended solids,

dissolved organic constituents, etc.) may create conditions that interfere with the mechanism of disinfection. To illustrate, the rate of kill of microorganisms by a particular disinfection process theoretically should be constant, in accordance with Chick's Law.⁷³ However, this kill rate may decrease if the organism to be destroyed is resistant to the disinfection process or there is material in the water that prevents the disinfectant from reaching the organism.

HEATING

Laubusch⁷³ states that "the important waterborne diseases are not known to be caused by spore-forming bacteria or other heat-resistant organisms, and therefore water can be disinfected by subjecting it to heat." More precisely, water can be made potable by heating it to its boiling temperature and then boiling it for 15 to 20 min. Although this method of disinfection can be effective, it is likely to be used sparingly by individuals and is not at all applicable on a large scale. The first reason for this is that boiling water does not meet the requirement that residual disinfectant be present to safeguard against recontamination (see criteria for appraising the suitability of a disinfection process for water cited by Laubusch⁷³). Additionally, boiling large amounts of water is neither convenient nor practical in the field because it would need to be performed frequently, it would require at least periodic monitoring at the individual level, and it would be very energy intensive if required on a large scale. Therefore, even though boiling water can be an effective disinfection process, it is probably most applicable in emergency situations.

IODINE

According to Laubusch,⁷³ the biocidal property of iodine and its use for rapidly "sterilizing" drinking water was proposed as early as 1915 by Vergnoux. Nevertheless, it was not until 1945, after four years of research (funded by the Office of Scientific Research and Development of the National Research Council) to find a process for destroying amoebic cysts and enteric bacteria in canteen water supplies, that Harvard University scientists concluded that iodine-containing compounds had the potential to be an effective disinfectant for canteen-water supplies under field conditions.⁷³ By 1945, as explained by Laubusch,⁷³ the globaline tablet (containing tetraglycine hydroperiodide and releasing 8 to 9 ppm of iodine (I_2) into a quart of water) was available. Globaline ($2[(NH_2CH_2\overset{\cdot\cdot}{\text{C}}OOH)_4HI] \cdot 2\frac{1}{2} I_2$)⁷⁴ was of value because it possessed a long shelf life, and because it was found that

one or two tablets dissolved in a quart of water in combination with a 10-min contact period would be effective in destroying enteric bacteria, amoebic cysts, and cercariae of schistosoma. However, the amount of disinfectant or the contact time should be increased as temperature decreases and/or color (an indication of the presence of interfering substances) increases.^{73,77}

As described by Laubusch,⁷³ adverse physiological effects associated with prolonged ingestion of iodine in the field were evaluated by the U.S. Army and Navy between 1949 and 1950. This study revealed no adverse effects from ingestion of as much as 12 to 20 mg/d of iodine over a 6-month period, and on the basis of a review of such data, the National Research Council recommended that the military could safely use a standardized iodine compound for the disinfection of individual drinking-water canteens. The military then accepted this recommendation and adopted globaline for field use. Gershenfeld⁷⁷ mentions that the military specifications for a single iodine water-purification tablet are that it contain approximately 20 mg of tetraglycine hydroperiodide, 90 mg of disodium dihydrogen pyrophosphate, and 5 mg of talc. Of particular importance to the military is that properly packaged and stored tablets containing these ingredients will be stable for extended periods at elevated temperatures.

Iodine chemistry in drinking water has been described in reviews of methods for disinfecting water by Laubusch⁷³ and the National Research Council.⁷⁸ The hydrolysis occurs according to the following chemical reaction:



The National Research Council⁷⁸ reports that the diatomic form of iodine (I_2) is relatively stable in aqueous solutions and it will predominate under neutral-to-acidic conditions (e.g., $\text{pH} < 7.0$). At a pH of 8.0 and titratable iodine concentrations between 30 and 0.5 ppm, however, Laubusch⁷³ points out that 20 to 90% of the I_2 that is present will be hydrolyzed to hypiodous acid (HOI). Furthermore, at pH levels greater than or equal to 9.0 and especially in the presence of phosphates, HOI will decompose rapidly to iodate (IO_3^-) and iodide (I^-), which results in a loss in disinfecting capacity.^{73,78} Moreover, even though the diatomic form of iodine (I_2) and hypiodous acid (HOI) are both germicidal, Laubusch⁷³ cites the results of studies published in the latter part of the 1950's that showed I_2 to be more effective against cysts than HOI (e.g., the cysticidal potency of I_2 was shown to be three times that of HOI at 6°C and twice that of HOI at 25°C), but HOI to be more viricidal than I_2 . To illustrate the cysticidal and viricidal efficiency of I_2 at 25°C for various contact times,

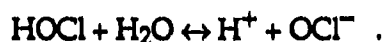
Laubusch⁷³ summarized the relevant results contained in these studies. Accordingly, for a given contact time (e.g., 10, 5, or 2 min), the amount of residual I_2 in ppm required to destroy viruses (i.e., 6.3, 13.6, and 34.0 ppm, respectively) is about twice that required to destroy cysts (i.e., 3.7, 6.0, and 12.5 ppm, respectively).

Laubusch⁷³ lists some of the major advantages and disadvantages of iodine as a disinfectant. Its major advantages include (1) not having its germicidal effectiveness reduced by ammonia and organic nitrogenous impurities, as is the case for chlorine; (2) having its disinfectant action be less dependent on contact time and temperature than is the case for chlorine; and (3) being effective against many microorganisms found in water, including spores, cysts, viruses, etc., within short times and at relatively low dosages. Major disadvantages include (1) the need for higher concentrations of iodine than chlorine to achieve comparable bacterial killing under similar conditions; (2) expense, with costs estimates as high as 20 times that for chlorine per unit of germicidal effectiveness; (3) the introduction of a slight taste and color change in the treated water, with the result that palatability and aesthetic quality are affected; and (4) limited understanding of the relative effectiveness of each form of iodine. The disadvantages related to cost and the introduction of a taste and color change in treated water are probably the reasons that iodine disinfection is not justified for uses other than for canteen water.

For disinfection of canteen water (i.e., 1 qt or 960 mL), military personnel are instructed to add globaline tablets.^{79,80} According to current military doctrine prepared by the U.S. Department of the Army^{79,80} each tablet is designed to release 8 mg/L (ppm) of iodine, and the minimum contact time required for disinfection is specified as 25 min; two tablets are recommended to ensure adequate disinfection for turbid or colored water. When chlorine is not available as a disinfectant for water being treated by a ROWPU operating in a bypass mode, we recommend that the maximum dosage of iodine be applied to those canteens being filled with such water.

CHLORINATION

The National Research Council⁷⁴ has reviewed the use and efficacy of chlorine as a disinfectant. Accordingly, the advantages of chlorination include (1) effectiveness as a microbiocide against most waterborne pathogens; (2) low cost and convenience to produce, store, transport, and use; and (3) high solubility in water. The chemistry of chlorine in water is illustrated by the following expressions:



Hypochlorous acid (HOCl) and hypochlorite ions (OCl^-) are termed "free chlorine"; and their concentrations are basically a function of pH. For example, at a pH between 7.0 and 8.0, HOCl dissociates into OCl^- . However, HOCl is a more effective biocide than OCl^- (e.g., 80 times more effective against E. coli and 150 times more effective against cysts of Entamoeba histolytica according to Lippy⁸¹ and because most potable waters that undergo disinfection range in pH from 7.0 to 8.0, higher doses of chlorine are generally required to achieve destruction of waterborne pathogens than would be needed at lower levels of pH.

In a review article, Lippy⁸¹ discusses the factors affecting the potency of chlorine as a disinfectant for bacteria, viruses, and protozoans. In this article the relationship between contact time and chlorine concentration (i.e., the produce of $C \times T$) is described for different levels of pH and temperature. Generally, the CT relationship increases with pH and is inversely proportional to temperature. Chemical interference results in the interaction of chlorine with nitrogen, sulfate, iron, and manganese, which combine with the chlorine to prevent it from reacting efficiently with waterborne pathogens. Physical interference is limited to organic particulates and not inorganic substances presumably because only organic material reacts with and consumes free chlorine thereby reducing its biocidal activity.^{74,81}

Sobsey⁷⁵ reports on the effectiveness of chlorine disinfection against different pathogenic organisms in water. Among the organisms considered are (1) bacteria such as E. coli, Salmonella spp., Shigella spp., Campylobacter jejuni, and Legionella spp.; (2) viruses such as rotaviruses, hepatitis A virus and virus indicators such as male-specific (F+) coliphages (e.g., M2); and (3) protozoan cysts such as Giardia lamblia and Cryptosporidium. The conclusions reached from these data are that some bacteria, including HPC, bacterial spores, mycobacteria, enteric viruses, and protozoan cysts are relatively resistant to free chlorine. Additionally, even bacteria that are generally sensitive to free chlorine can become more resistant under certain conditions such as bacterial growth under low nutrient levels. However, recent data show that rotaviruses, hepatitis A virus, and male-specific (F+) coliphages (e.g., M2) can be inactivated by free chlorine, even though these viruses are more resistant to inactivation than most enteric bacteria.

Among the most resistant organisms identified by Sobsey⁷⁵ were Norwalk virus and Cryptosporidium. Norwalk virus was found not to be completely inactivated at chlorine

concentrations capable of disinfecting poliovirus and human rotavirus Wa (i.e., a free chlorine concentration in the range from 3.75 to 6.25 mg/L and a contact time of 30 min). However, Norwalk virus was inactivated by a concentration of free chlorine of 10 mg/L. The coccidian protozoan, Cryptosporidium, was even more resistant to free chlorine concentrations typically capable of disinfecting sources of drinking water. For example, Sobsey⁷⁵ indicated that in one study involving Cryptosporidium (which was conducted in a phosphate-buffered saline solution at a temperature of 4°C and a pH of about 7) a free chlorine concentration of 30,000 mg/L and a contact time of 18 h inactivated only about 95% of the organisms. Nevertheless, according to Rose,⁸² the true efficacy of chlorine disinfection on Cryptosporidium in water is not really known because the data for inactivation of Cryptosporidium cited by Sobsey⁷⁵ are from the only study in the literature that included an investigation of the effect of sodium hypochlorite on Cryptosporidium and that study did not present data with regard to oocyst inactivation under controlled water disinfection conditions.

Kenyon⁸³ drew the following conclusions from the results of a study to determine free available chlorine (FAC) disinfection criteria for primary drinking water supplies at fixed army installations: "Potable water supplies less than pH 9 and and warmer than 6°C may be safely disinfected by a FAC dose of 1 mg/L for a minimum contact time of 30 min. For cold waters ($\leq 6^\circ\text{C}$) a FAC dose of 2 mg/L is recommended." Also, these dosages were found to inactivate even coxsackie B3 virus (an enterovirus) at a pH of 9 and because most waters do not have such a high pH, a safety factor is incorporated into the recommended dosages. Furthermore, Kenyon⁸³ suggests that if contact times longer than 30 min are available, then FAC dosages may be lowered.

In recent years concerns about health risks associated with the byproducts of chlorination, such as trihalomethanes (e.g., chloroform), have stimulated the search for alternatives to chlorine disinfection.⁷⁴ A discussion of the byproducts of chlorination is provided by Rechow and Singer.⁸⁴

Williams *et al.*⁸⁵ and Worley and Williams,⁸⁶ who were supported in part by funding from the U.S. Army Medical Research and Development Command at Fort Detrick, in Frederick, MD, describe the results of their research on N-halamine compounds as alternatives to chlorine. One such compound, 3-chloro-4,4-dimethyl-2-oxazolidinone (nicknamed compound I), was found to be effective on all organisms against which it was tested at low concentrations.⁸⁶ However, a longer contact time is required for this compound to inactivate most organisms than is required for a comparable concentration of free chlorine. Consequently, a small amount of free chlorine to provide rapid initial

disinfection is applied with compound I. The principal attribute of compound I, however, is that it is very stable in water, especially in the presence of organic demand, which would consume chlorine. Thus, compound I in combination with a small amount of free chlorine has promise as a very effective alternative to chlorine disinfection, particularly for water traveling long distances in water distribution systems.

Currently, chlorination remains the most effective and convenient proven method available to the military for disinfecting large quantities of water for consumption by military personnel in the field. Under emergency conditions, such as may exist when a ROWPU is forced to operate in its bypass mode (i.e., RO components cannot be used), the dosage of chlorine used for disinfection should be the same as that recommended in the field for disinfecting untreated (raw) water in water-sterilizing bags (commonly referred to as Lyster bags) or water stored for the purpose of filling canteens. Accordingly, enough chlorine should be added to the raw water so that the total-available residual chlorine concentration (i.e., the sum of free-available chlorine and chlorine in combination with ammonia or organic nitrogen compounds—combined-available chlorine), after 30 min of contact time, will be at least 5 mg/L.^{79,80} However, as noted earlier, certain raw-water conditions such as the presence of especially resistant organisms, a $\text{pH} \geq 8$, particularly cold water, or water containing large amounts of organic material may require more than normal chlorination for adequate disinfection. The command surgeon will need to designate when conditions warrant higher than normal chlorine residuals, and consequently when higher than normal chlorine dosages are necessary to meet such requirements. As just mentioned, such conditions are likely be associated with emergency situations where the available source of potable water is either untreated (i.e., raw-water) or only partially treated (e.g., bypassing of RO components).

ANALYTICAL METHODS

The U.S. Army, as well as other military branches, uses Water Quality Analysis Sets (WQAS) to determine the treatability of raw waters and/or to monitor the performance of water-purification systems. These sets are a collection of individual water-test kits arranged into two separate units, an Engineer Set and a Preventive Medicine Set.⁸⁷ The Engineer Set is used in water-source selection. It provides information on chemical contamination and helps determine the type of purification equipment required. The Preventive Medicine Set

is designed for on-site monitoring of the quality of raw-water sources and drinking water produced.

The WQAS were developed in 1972 to replace the World War II era Water Quality Control Set (WW II WQCS) and entered the supply system in early 1979. However, the results of a recent evaluation of the WQAS indicated that many of the test kits available in the sets are nonessential and that the system has a number of shortcomings, such as excessively time-consuming analytical procedures.⁸⁸

The Army now employs new-generation water-purification processes, such as reverse osmosis, which require rapid and accurate analysis of raw and treated water. The required sensitivity for such analyses is greater than that for earlier generations of water-purification equipment. Foster-Miller, Inc. (Waltham, MA)⁸⁹ has developed a prototype Water-Quality Monitor (WQM) under contract with the U.S. Army to meet the needs of the new water-purification system. The WQM is being evaluated as a potential substitute for the WQAS.

The U.S. Army field-water-quality standards and capabilities of the WQAS and proposed WQM are shown in Table 13.⁹⁰ Discussions of the available analytical methods for some of these substances are those of military concern, presented in Volume 4 of this report. Generally, wet-chemistry procedures exist for the analysis of As, CN^- , Mg^{+2} , Cl^- , and SO_4^{2-} .⁹¹

COMPARISON OF WQAS AND WQM

A comparison is made here between older WQAS equipment and more recently developed WQM equipment.

Physical Characteristics

The WQAS weighs in excess of 55 lb, occupies approximately 4.4 ft³, and uses wet chemistry in the analytical procedures.¹ The prototype WQM weighs 28 lb, occupies only 1.4 ft³, and it combines commercially available state-of-the-art electronic monitoring instrumentation with a powerful microprocessor.⁹² A measurement routine that includes pH, temperature, TDS, turbidity and free-available-chlorine residual can be completed in less than 3 min with the WQM, as compared to 45 to 60 min for the WQAS. The elimination of wet-chemistry analyses is expected to reduce potential human error.

Table 13. U.S. Army field-water-quality standards and capabilities of Army water-quality-analysis sets.^a

Constituent	Standard ^b	Analytical capabilities ^c		
		WQAS PVNT MED set	WQAS engineer set	Water- quality monitor ^d
Acidity (mg/L)	none	0 to 500	none	none
Alkalinity (mg/L)	none	none	0 to 500	none
Ammonia-nitrogen (mg/L)	none	0 to 2	none	none
Arsenic (mg/L)	0.2	none	AN-M2 ^e	M272
Chloride (mg/L)	600	1,000 to 20,000	1,000 to 1,500	none
Color (units)	50	none	0 to 500	none
Cyanide (mg/L)	2	none	AN-M2 ^e	M272
Dissolved oxygen (mg/L)	none	0 to 15	none	none
Fluoride (mg/L)	none	0 to 2	none	none
Free chlorine residual (mg/L)	5	none	0.1 to 10	0 to 15
Hardness (mg/L) (Ca and Mg)	none	none	0 to 9,000	none
Iron (mg/L)	none	0 to 10	none	none
Magnesium (mg/L)	150	none	see hardness	none
Nitrate-nitrogen (mg/L)	none	0 to 30	none	none
pH	none	4 to 10	3 to 11	0 to 14
Sulfate (mg/L)	400	0 to 150 ^f	0 to 3,000	none
TDS (mg/L)	1,500	none	0 to 50,000	0 to 50,000
Temperature (°F)	none	-30 to 120	none	25 to 160
Turbidity	5 NTU	0 to 500 FTU	5 to 200 JTU	
Zinc (mg/L)	none	0 to 10	none	

^a Adapted from Lund.⁹⁰^b Standards extracted from Appendix G, TB MED 229.⁹³^c Capabilities of sets listed on pp. 2-15 and 2-52, TM 5-6630-215-12.⁸⁷^d Adapted from Table 7 of Standard Methods.⁹¹^e The AN-M2 kit is scheduled to be replaced by the M272 Water Testing Kit, Chemical Agents.^f Sample dilution increases range to 1500 mg/L.

Analytical Capabilities:

The analytical capabilities of the WQAS and WQM equipment are summarized next.

Water-Quality-Analysis Sets (WQAS):

The main components of the WQAS-Engineer Set are

1. Alkalinity test kit
2. Turbidity test kit
3. Sulfate test kit
4. pH and chlorine residual test kit
5. Hardness test kit
6. Color test kit
7. Low-range chloride test kit
8. TDS - conductivity meter
9. Water testing kit for chemical agents, AN-M2
10. Refill kit, chemical detector, V-G, ABC-M30
11. Supporting labware and reagents.

The existing turbidity kit does not meet the Material Needs Document requirement for measuring turbidity in the range of 0.1 to 0.5 unit.

The main components of the WQAS-Preventive Medicine Set are as follows.

1. Acidity test kit
2. High-range chloride test kit
3. Iron test kit
4. Dissolved-oxygen test kit
5. Zinc test kit
6. Multipurpose spectrophotometer
 - a. Fluoride
 - b. Nitrogen, ammonia
 - c. Ferrous iron
 - d. Ferric iron

In the recent evaluation of the WQAS, the following test kits were found to be nonessential for use in the field in relationship to the mission of the military units:⁸⁸

- | | | |
|------------|-------------|---------------------|
| 1. Acidity | 2. Chloride | 3. Dissolved oxygen |
| 4. Zinc | 5. Fluoride | 6. Ammonia |
| 7. Sulfate | 8. Hardness | 9. Color |

Water-Quality Monitor (WQM):

The WQM is designed to evaluate the effectiveness of the Reverse Osmosis Water-Purification Units (ROWPU's) by measuring the following parameters:⁹²

1. Temperature
2. pH
3. Turbidity
4. TDS
5. Free-available-chlorine residual

The parametric specification in terms of range and sensitivity are presented in Table 14.

The WQM is divided into two compartments:

- (a) Electrical compartment, and
- (b) Sensor and accessories compartment.

The electrical compartment houses the electrical circuitry, microprocessor, operating controls, battery, displays, and connecting terminals. Measurement sensors, power cord, and accessories for field calibration and field maintenance are housed in the sensor and accessories compartment.

Calibration of the sensors for all five parameters must be performed in the laboratory every six months or when one of the following conditions exists:⁸⁹

- The WQM is new.
- Any internal electronics have been replaced.
- Either of the sensors has been replaced.
- A calibration offset exceeds its maximum value.
- WQM readings appear incorrect.

Conductivity is used to determine TDS. Imbedded transformer coils are used in lieu of electrodes because the coils do not foul as readily as the more conventional electrodes. The conductivity meter is calibrated in the field by placing the calibrate/measure switch in the calibrate position, keeping the probe sensor dry, and pressing the activate button. The

Table 14. Specifications for WQM parameters.^a

Parameter	Range	Sensitivity
Fluid temperature (°F)	25 to 160	% 2.0
Fluid temperature for remaining parameters (°F)	25 to 120	—
pH	0 to 14	% 0.5
Total dissolved solids (TDS) (mg/L)	0 to 1,000 1,000 to 10,500 10,500 to 50,000	% 50 % 500 % 2,500
Turbidity (NTU)	0 to 150	% 10
Residual chlorine (mg/L)	0 to 15	% 1.0

^a Adapted from Rubin *et al.*⁹²

TDS range-selector switch has three positions that correspond to the following TDS concentration ranges:

Range-selector switch position	TDS concentration range (ppm)
L	0 to 1,000
M	1,000 to 10,000
H	10,000 to 50,000

The conductivity cell is calibrated against a NaCl solution for each of the concentration ranges. This is an appropriate approach for the evaluation of TDS in the product water of the 600-gph ROWPU because the product water should contain primarily NaCl when demineralizing ocean and estuarine waters. The NaCl solution should not be used for any other water if a precise and accurate TDS determination is desired.

Free-chlorine residuals are measured amperometrically.⁹² The sensor is similar to a conductivity cell but is separated from the bulk sample by a chlorine-permeable membrane. Field calibration of the sensor is performed by setting the calibrate/measure switch in the calibrate position and pressing the activate button. The residual-chlorine housing contains water which, when attached to the sensor, keeps the chlorine membrane wet at all times. During operation, the residual-chlorine sensor is separated from its housing. A 10-min

warm-up period should be provided before calibrating the residual-chlorine circuitry. All other calibrations can be performed after a 2- to 3-min warm-up period. The sensor must be immersed in solution 30 s prior to each sample measurement.

Laboratory calibration of the residual-chlorine circuitry can be somewhat more complex than the laboratory routines used to calibrate the other types of sensors. Calibration is normally performed using the following procedure:⁸⁹

- Turn selector switch to chlorine.
- Place measure/calibrate switch in calibrate mode.
- With the residual-chlorine sensor in its housing containing deionized water, alternately press the "activate" button and adjust the zero potentiometer until the digital display gives the closest possible reading to 0.0.
- Place "measure/calibrate" switch in measure mode.
- Remove sensor from housing and place in tank of chlorinated water (30 gal) containing 15 mg/L of free-available chlorine.
- Move sensor in circular motion for 30 s. While still moving the sensor, press the activate button and adjust coarse-standardize potentiometer to obtain a digital display to within 10% of the correct chlorine reading in mg/L.
- Alternately press the activate button and adjust fine-standardize potentiometer to obtain a digital display to the nearest correct reading.

If appropriate calibration sensitivity is not attained using the above procedure, further electrical calibration will be required. It is claimed⁸⁹ that annual or biannual calibration may be sufficient to maintain the sensor's sensitivity within ± 1 mg/L free-chlorine residual.

Mr. G. Clifford White, engineering consultant, San Francisco CA, reviewed the method used to determine free-available chlorine.⁹⁴ The free-chlorine analyzer selected for the WQM (Foster-Miller, Inc., Waltham, MA) is a Uniloc polarographic membrane-type unit (Rosemount Analytical-Uniloc Division, Irvine, CA). Some of the performance characteristics of this sensor reported by Mr. White are as follows:

- The sensor electrolyte should be replaced every two or three months, rather than six months, as implied in the general WQM maintenance-calibration procedures stated previously. The sensor then has to be recalibrated.

- The sensor should be examined at periodic intervals to make sure it is clean. To determine this interval, the sensor should be examined after 7 d of operation and then at longer intervals if necessary. The sensor can be cleaned relatively easily by washing with clean water, and if coated, by wiping gently with soft tissue or cotton cloth.
- The water has to be replenished near the membrane; otherwise, the chlorine will be depleted. It is assumed that adequate provision has been made for water recirculation in the design of the WQM module.
- The percentage of total free chlorine (hypochlorous acid, HOCl) plus hypochlorite ion (OCl^-), measured by the Model 453 membrane sensor, varies widely with the pH and temperature of the water because only a small portion of the OCl^- ion diffuses through the membrane. We assume that the WQM microprocessor can automatically correct for the output of the membrane sensor.
- According to the manufacturer of the free-chlorine-residual probe, the sensor requires extensive on-line operation before it becomes stabilized (approximately 24 h). However, we assume that the circuitry has been redesigned in product improvement for the WQM to give the 10-min warm-up time advertised by the manufacturer of the WQM.
- After consultation with users of the residual-free-chlorine membrane sensor, Mr. White recommends that the probe be calibrated on-site against the actual free-chlorine level in the treated water, in preference to using standard solutions of chlorine-demand-free water in the laboratory, as proposed by the manufacturer of the WQM. If the U.S. Army insists on using the FACTS (free-available-chlorine tests, syringaldazine) colorimetric method for free-chlorine analysis, then the free-chlorine residual must be measured with a filter photometer or spectrophotometer, as described in Standard Methods.⁹¹ Alternatively, a portable amperometric titrator using the forward titration method, as described in Standards Methods,⁹¹ would prove to be faster, more accurate, and with fewer complications compared to the FACTS method with a spectrophotometer or filter photometer.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Disinfection bears the burden as the primary defender against the transmission of waterborne diseases. Filtration serves as a secondary barrier, but it never can be trusted to provide safe drinking water under all circumstances. It is apparent, however, that increasing the removal of microorganisms in the filter decreases the reliance on disinfection.

Turbidity is commonly believed to be an important adjunct to disinfection efficiency because the colloids and suspended solids can shield the pathogens from the disinfectant. Unfortunately, this hypothesis has never been demonstrated in practice except for the grossest contamination with fecal matter. In addition, the organic portions of the particulate matter may exert a chlorine demand and thereby decrease the disinfecting power of the disinfectant.⁹⁵

The removal of turbidity in deep-bed filters does appear to be related to the removal of microorganisms. The degree of removal, however, is also important. For example, a 90% removal of turbidity may suffice to meet a drinking-water standard, but a 90% removal of a microorganism is for all practical purposes inconsequential. With this in mind, the performance of deep-bed direct filtration will be compared with the more conventional treatment used in the 3000-gph MWPU.

DIRECT FILTRATION

The main pretreatment unit of the 600-gph ROWPU represents a mode of operation called direct filtration without in-line flocculation. The filter is a deep-bed type containing several layers of media with different properties. Such filters are called mixed-media or multimedia filters.

THEORETICAL REMOVAL OF PARTICLES IN THE 600-GPH ROWPU MULTIMEDIA FILTER

The single-collector theory for deep-bed filtration was discussed in detail in a previous section of this report. The theory is based on the assumptions that completely destabilized particles always stick to the filter media, but do not flocculate as they move through the filter bed. The theory grossly underestimates the chances that the particle will

be collected in a stacked bed of collectors, but the general change in the collector efficiency with particle size is believed to be correct as illustrated in Fig. 5.

This theory was used to estimate the removals of isolated, completely destabilized, nonflocculating particles passing through the multimedia filter installed in the current 600-gph ROWPU. The dimensions of the collectors used in the calculations were those listed in Fig. 8, except that the collectors were assumed to be of uniform size in each layer. The water temperature was assumed to be 20°C, and the specific gravity of the particles was held constant at 1.01 (the results proved not to be very sensitive to particle density). The filtration rate was set at the following two values: the current 7.0 gal/(min • ft²) (ROWPU feed-water flow = 34.5 gal/min) and the minimum of 4.6 gal/(min • ft²) (feed-water flow = 22.5 gal/min) that the RO section of the ROWPU can accept without excessive concentration polarization, as shown in Volume 7 of this report. The results are shown in Fig. 19.

Particles with sizes around 2 mm will be removed the least by the multimedia filter, and particles greater than about 20 mm should be removed almost completely. The cysts of pathogenic protozoans may or may not be well removed because removal increases rapidly with particle size in the region of about 5 to 30 mm, which is the size range for most cysts. Finally, decreasing the filtration rate from 7.0 to 4.6 gal/(min • ft²) does not increase the ability of the filter to remove cyst-sized particles (see Fig. 19), although the filtered-water turbidity should be decreased somewhat.

Observed Removals of Microorganisms

A few studies have been performed on the removals of Giardia muris cysts (5 to 13 mm) or cyst-sized particles with direct deep-bed filtration. With the sole exception of the study by Duncan,⁴⁸ relatively nonturbid feed waters were used in most of these studies. Logsdon et al.³³ believe that the removal of G. muris cysts or cyst-sized particles is closely related to the turbidity of the filtered water. For example, more than 99.5% of the cysts was removed when the filtered-water turbidity was less than about 0.3 NTU in one series of experiments. Cyst removal decreased to 59% or even less in some experimental runs where the filtered-water turbidity was well in excess of 0.3 NTU. In another series of studies, Logsdon et al.³³ report removal of cyst-sized particles in excess of 99% for filtered-water turbidities of less than 0.10 NTU. Again the filter performance decreased when the filtered-water turbidity exceeded 0.10 NTU.

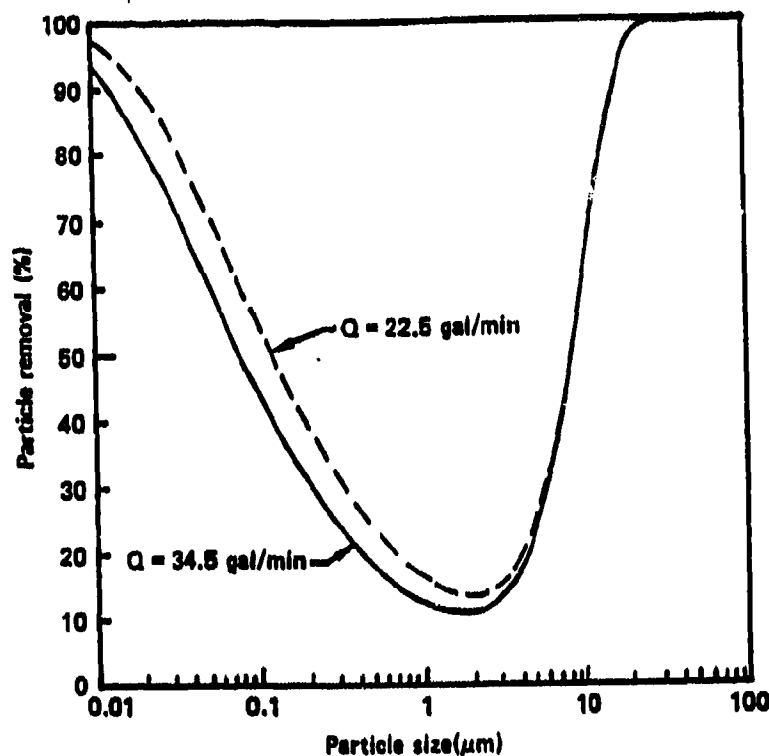


Figure 19. Theoretical removal of destabilized particles in the 600-gph ROWPU multimedia filter. Q = feed-water flow rate.

It should be pointed out that the *G. muris* cyst studies described by Logsdon *et al.*³³ were for a feed water coagulated with alum, or alum plus a polymer, and then flocculated for 20 to 30 min prior to filtration. This approach differs greatly from that used in the 600-gph ROWPU and is considerably more rigorous. Studies more or less paralleling the mode of operation used in the ROWPU are those reported by Cleasby *et al.*⁴⁷ and Duncan.⁴⁸

The average removal efficiency of cyst-sized particles (7 to 12 μm) observed by Cleasby *et al.*⁴⁷ was 97.5% for alum coagulation, and about 91% for coagulation with a cationic polyelectrolyte (Cat-Floc T). The feed water was not flocculated after coagulation in a static flash mixer, and the filtration rates utilized in the study were relatively modest [2.8 to 5.5 gal/(min \cdot ft²)]. Those investigators also related filter performance to the raw-water turbidity rather than the filtered-water turbidity. The reported removals were for waters containing less than 16 NTU of initial turbidity and "small" algae populations, or less than 11 NTU of turbidity and "moderate" algae populations.

Duncan⁴⁸ determined the removal of Saccharomyces cerevisiae yeast cells (6 to 18 μ m) from highly turbid feed waters (50 and 120 NTU) with a direct-filtration process duplicating that used in the 600-gph ROWPU. The removal of S. cerevisiae cells across the multimedia filter averaged about 84% for a feed-water pH of 5.5, and about 94% for a feed-water pH of 9.5. Details relative to the coagulation procedures used in the study were not given in the preliminary study report, but the Cat-Floc coagulant was probably Cat-Floc T1, and the dosage was probably held constant at 5 mg/L. The removal of the cysts reported for these high-turbidity waters appears reasonable considering the fact that the coagulant dose probably was not optimal.

According to single-collector theory, the removal of bacteria by deep-bed filters should be less than the removal of cysts as shown in Fig. 19. This can also be concluded from the results of direct-filtration studies performed with bacteria removal used as a measure of process performance. For example, Logsdon and Fox³² observed total coliform-bacteria removals of 97.7 to 99.2% for filtered-water turbidities of less than 0.3 NTU. These results may be compared with the >99.5% removal reported for the G. muris cysts with the same low filtered-water turbidities. Two other examples where the removals of bacteria and cyst-sized particles were determined simultaneously on the same feed water were the following: (1) 91% removal of total-coliform bacteria with alum coagulation, as compared to 97.5% removal of cyst-sized particles (Cleasby *et al.*⁴⁷), and (2) an overall-average bacterial removal of about 75%, as compared to a S. cerevisiae cell removal of about 94% at a pH of 9.5 (Duncan⁴⁸).

The removal of completely destabilized virus particles should be somewhat better than the removal of bacteria-sized particles. This proved not to be the case for the only study reviewed herein in which various bacteria (E. coli, total aerobic and total enteric) and poliovirus, Mahoney Type I, were filtered simultaneously from the same feed water (Small *et al.*¹). The removal of the virus across the multimedia filter of the ROWPU was reported to be about 74% for a feed-water pH of 7.6 to 8.5, whereas the overall average bacterial removal was about 83%. The virus particles may not have been completely destabilized because the optimum coagulant dose was not ascertained in that study. Robeck *et al.*³⁹ obtained 98%+ removal of poliovirus Type I when river and ground waters were coagulated with alum and filtered directly through a dual-media filter at a rate of 6 gal/(min \cdot ft²). The feed-water pH was always close to 8.0 (7.7 to 8.1), and the alum dosage was carefully adjusted to yield maximum turbidity removal. The best virus removal was obtained for filtered-water turbidities of less than 0.5 JTU.

The removal of turbidity, relatively poor immediately after filter backwashing and cleaning, increased with run time (i.e., filter "ripening") in nearly all of the direct-filtration studies reviewed herein. For example, Small *et al.*¹ observed that the average filtered-water turbidity decreased from about 1.3 NTU immediately after start-up to 0.8 NTU after 3 h of operation for the direct-filtration system used in the 600-gph ROWPU. The average filtered-water turbidity then decreased at a slower rate to about 0.6 NTU after 9 h of run time. Presumably, the removal of the microorganisms also increases as the filter ripens. This was observed by Cleasby *et al.*⁴⁷ for total coliform bacteria and cyst-sized particles, as well as by others (Logsdon and Fox³²).

Limits on Process Applicability

It has long been recognized that direct filtration with dual-media filters is appropriate only for good-quality raw waters, but just how good was not known. The maximum limits on certain raw-water constituents recommended recently by various authorities for direct filtration are summarized in Table 15. Some hope was expressed by an American Water Works Association (AWWA) Task Group⁴⁰ in 1980 that the process could be used to treat very turbid waters successfully by adding a third layer of fine garnet to the dual-media beds employed at the time. This was not substantiated by subsequent experience, as evidenced by the work of McCormick and King⁴⁵ and the recommendations of Trussell *et al.*⁴¹ presented in this report. It was also recognized, early on, that algae cause considerable difficulties with the process, and especially bluegreen algae.⁴³ The maximum recommended raw-water turbidity appears to stabilize around 10 to 15 NTU for filtration rates in the neighborhood of 5 gal/(min • ft²). Rebhun *et al.*⁴⁴ also noted that color will also pass readily through a filter if present in too great a concentration in the untreated water.

Filter-Bed Composition

The consensus appears to be that the depth and effective size of the calcined-aluminum-silicate layer used in the ROWPU multimedia filter (shown in Fig. 8) is appropriate for multimedia beds. The depth of the anthracite layer is also adequate but the effective size of 0.80 mm is too small, and the uniformity coefficient of 2.0 is too large. The trend today is for an effective anthracite size in the range of 1.1 to 1.5 mm, and a uniformity

Table 15. Summary of recommended maximum limits on raw-water-quality characteristics for direct filtration (gravity filters).

Item	AWWA (1980) ^a	McCormick and King (1982) ^b	Cleasby <i>et al.</i> (1984) ^c
Type of filter	generally dual-media	dual- and multimedia	dual-media
Filtration rate [gal/(min • ft ²)]	1 to 6	5 to 8	2.8 to 5.5
Type of coagulant	all types	cationic polyelectrolytes including Cat-Floc T1	Cat-Floc T
Quality constituent			
Turbidity	5 FTU	10 NTU	16 NTU ^e
Turbidity	500 FTU ^d	—	11 NTU ^f
Color	400 Hazen units	15 APHA units	—
Color	1000 Hazen units ^d	—	—
Iron	0.3 mg/L	—	—
Manganese	0.05 mg/L	—	—
Algae	2000 asu/mL	1000/mL	—

^a Adapted from AWWA (American Water Works Association).⁴⁰

^b Adapted from McCormick and King.⁴⁵

^c Adapted from Cleasby *et al.*⁴⁷

^d According to reports of a few industrial plants for multimedia filters containing a garnet layer (0.2 to 0.3 mm).

^e For small algae population.

^f For moderate algae population.

coefficient as small as possible (AWWA report,⁴⁰ McCormick and King,⁴⁵ Cleasby *et al.*,⁴⁷ Logsdon *et al.*³³).

CARTRIDGE FILTERS

Cartridge filters with a 5-mm size rating are installed downstream from the ROWPU multimedia filter. The results of studies performed by Small *et al.*¹ demonstrate that those filters do not remove viruses or bacteria adequately. It was hoped that the cartridge filters would prove to be an effective barrier against the transmission of protozoan cysts. When

Long⁴⁹ ran tests using various size-rating cartridge filters (1 to 10 mm), the results were inconclusive. Some of the cartridge filters tested removed virtually all of the 5.7-mm beads added to the feed water as a cyst analogue, and others removed virtually none.

DIATOMACEOUS-EARTH (PRECOAT) FILTRATION

A number of studies performed on the removal of microorganisms and particles with the precoat-type filter demonstrates that the filter essentially strains the particles from the water when no coagulant is added to the precoat or the filter feed water. Large particles are well removed but fine particles are not removed. Because most of these studies used very clean waters (tap water, distilled-deionized water, etc.), the problem of maintaining cake porosity with turbid waters was not addressed. The filtration rates investigated commonly were in the range of 1 to 2 gal/(min • ft²).

Protozoan cysts and cyst-sized particles are well removed without a need for a coagulant. Baumann and Babbitt⁶⁶ demonstrated that a filter septum with 18.6-mm openings will remove nearly all of the cysts of *E. histolytica* without a diatomite precoat. Coarser septa with a diatomite precoat and body feed will remove 99.8% of the cysts of *G. muris* and 99.9% of 9-mm-diameter spheres (Logsdon *et al.*⁶⁷). A minimum removal of 99.03% was noted by DeWalle *et al.*⁶⁸ in one experimental run out of a total of twelve for the cysts of *Giardia lamblia*. The removals were much better for the remaining eleven runs. Finally, Jones and Brady⁶⁵ found that a precoated filter without body feed was able to remove most of the cercariae of *Schistosoma mansoni*.

It was noted by several of those investigators that the removal of protozoan cysts did not correlate with the removal of turbidity. This tends to support the contention that a diatomaceous-earth filter acts more as a strainer than a deep-bed filter. It was also noted by both Logsdon *et al.*⁶⁷ and DeWalle *et al.*⁶⁸ that the removal of the cysts and cyst-sized particles tended to increase with filter run time when a body feed was utilized. This suggests that some of the cysts are removed within the filter cake, as well as on the surface.

The removal of bacteria achieved with precoated filters has varied with the grade of diatomite used to coat the filter septum, as well as the investigator reporting the results. A 60 to 90% decrease in total microscopic counts was reported by Syrotynski and Stone⁵⁵ for a filtration rate of 1 gal/(min • ft²). In that study, body feed was used and no correlation of bacterial removal with turbidity removal was noted. According to Hunter *et al.*,⁵⁶ the removal of total-coliform bacteria increased from about 90% for the coarsest grade of diatomite investigated to 99.86% for the finest grade. Lange *et al.*⁶¹ also found that the

removals of total coliforms and total plate-count bacteria increased with the finer grades of diatomite, but the removal of total coliform bacteria was in the range of only 30 to 70%.

Burns *et al.*⁵⁷ found that the removal of 0.45- to 1-mm clayey particles was virtually nil. Amirhor and Engelbrecht⁶⁰ report little removal of the bacteriophage MS2 at pH values of 6, 7, and 8 and a filtration rate of 1 gal/(min • ft²).

It was noted early in the development of precoat filters that coating the diatomite with alum improved the removal of suspended solids.⁵¹ Cationic polyelectrolytes were eventually substituted for the alum and research proceeded in this vein for a number of years. Finally, people tried adding the coagulant to the feed water, instead of the filter media, with equally good results as long as the particles were completely destabilized. Some examples of improvement in process performance with the use of coagulants follow.

The removal of 0.45- to 1-mm clayey particles increased from virtually nil to almost complete when the filter aid was coated with a cationic polyelectrolyte.⁵⁷ The removal of the bacteriophage MS2 increased from virtually nil to greater than 90% when the filter aid was coated with a cationic polyelectrolyte, or when the polymer was added in appropriate amounts to the feed water.⁶⁰ The removal of bacteriophage T2 and poliovirus Mahoney Type I exceeded 98% when the filter aid was coated with a cationic polyelectrolyte, or when the polyelectrolyte was added to the feed water.^{58,59} Finally, the relatively poor total-coliform bacteria removal of 30 to 70% reported by Lange *et al.*⁶¹ increased to 96 to 99.9% when the filter aid was coated with alum.

THE ROWPU BYPASS

Some of the data collected on the removal of various microorganisms and turbidity by the pretreatment units of the 600-gph ROWPU and the 3000-gph MWPU are summarized in Table 16. The MWPU can decrease the turbidity of a river water from an average of 50 NTU to <0.2 NTU, provided that a well-defined sludge blanket is maintained in the ERDLATOR. The corresponding decrease in the total-coliform bacteria was about 99.9%. No information was found in the literature relative to the removal of protozoan cysts with the MWPU, but in light of the findings of others concerning the removal of cysts with precoat filters, it can be safely assumed that nearly all of the cysts are removed, even when the ERDLATOR is not functioning properly. The ancient MWPU provides an effective secondary barrier against the transmission of waterborne diseases.

According to Table 16, the apparatus contained in the pretreatment section of the ROWPU should be able to treat a water with an initial turbidity ranging from 3 to 7 NTU

Table 16. Comparison of the performances of the multimedia filter of the 600-gph ROWPU with that of the 3000-gph MWPU when operated in accord with Army operation manuals -- no prechlorination.

Item	600-gph ROWPU (1982) ^a	3000-gph MWPU (1967) ^b	(1958) ^c
<u>Feed water</u>			
Turbidity (NTU)	2.2 to 7.1	44 to 59	"pond water"
Temperature (°C)	10 to 24	15 to 26	2
pH	7.6 to 8.5	7.7 to 8.2	7.2 to 7.6
<u>E. coli</u> (cfu/mL)	14 to 8500	--	--
Total plate count (cfu/mL)	354 to 24,290	--	--
Total coliforms (number/mL)	--	5.8 to 107	--
<u>Spores:</u>			
<u>B. globigii</u> (cfu/mL)	220 to 15,000	--	--
<u>B. subtilis</u> (cfu/mL)	--	--	3200 to 6000
<u>Passage through filters (%)</u>			
Turbidity	16	<0.4 (<0.2 NTU in filtered water)	NR ^d
<u>E. coli</u>	9	--	--
Total plate counts	26	--	--
Total coliforms	--	<0.11	--
<u>Spores:</u>			
<u>B. globigii</u>	2	--	--
<u>B. subtilis</u>	--	--	0.37

^a Adapted from Small *et al.*¹ The percent passages shown do not include the removal observed in the cartridge filters, which in most cases was negligible.

^b Adapted from Lindsten and Schmitt.⁷¹

^c Adapted from Pruett and Lindsten.⁷⁰

^d NR = not reported.

adequately. This was not the case according to the results summarized in Table 16. The multimedia filter removed on the average only 84% of the turbidity, and 74 to 98% of the bacteria shown in Table 16. Cysts were not investigated, but the removal of the cysts probably would have proven better than the removal of the bacteria. Even so, the odds are that some of the cysts would have passed through the filter.

The performance of the ROWPU multimedia filter was less than one might expect for the relatively low-turbidity river water tested. The reasons for this may be an improper coagulant dose and inadequate mixing, as discussed subsequently.

Considering the unusual hazards faced by Army personnel in all possible climates, it would seem reasonable that a filtering system should be provided to remove essentially all protozoan cysts and other large parasites. Theory and practice indicate that the multimedia filter installed in the ROWPU will never accomplish this task, even with perfect particle destabilization, and the performance of the cartridge filters appears to be unreliable at this time. Considering these factors, we recommend that the RO section of the ROWPU should not be bypassed until it is known for certain that the cartridge filters will remove cyst-sized particles reliably under all circumstances. This recommendation is even more important because of recent evidence⁹⁶ strongly suggesting that the microorganism Cryptosporidium, a small (2 to 6 μ m) protozoan parasite with oocysts (containing infective sporozoites) that appear to be (1) resistant to the disinfectants used routinely in hospitals and laboratories (e.g., in laboratory studies at Auburn University in Alabama, disinfection normally involves the use of full-strength commercial bleach)⁹⁷ and (2) capable of deformation such that they can pass through cartridge-filter pore diameters greater than 2 to 3 μ m in size,⁹⁸ belongs on the list of waterborne organisms capable of producing outbreaks of gastroenteritis in humans (symptoms include diarrhea and abdominal cramps that can last from 1 to 25 d).

COAGULATION CONTROL

The failure to provide the optimal coagulant and water conditioner to the ERDLATOR becomes readily apparent to the operator because a well-defined sludge blanket cannot be maintained. The pretreatment units of the 600-gph ROWPU, on the other hand, represent a good example of "out-of-sight, out-of-mind" operation. The units are operated under pressure, and any turbidity escaping the pretreatment units is deposited on the RO membranes. The processed water is of good quality even when the pretreatment units are not functioning properly. This may seem to be a positive attribute of the ROWPU, but the life of the RO elements will be shortened significantly under such conditions of turbidity deposition on the membranes.

The amount of coagulant added to the water has to be just right, neither too large nor too small. Unfortunately, the effect of off-doses of coagulant on the performance of a deep-bed filter operated in the direct-filtration mode has not been investigated extensively.

Habibian and O'Melia³⁶ demonstrated that off-dosages of a Cat-Floc polyelectrolyte amounting to plus or minus an order of magnitude causes a complete deterioration in filter performance as shown in Fig. 17. Somewhat similar results were reported by Adin and Rebhun³⁵ for kaolinite turbidity and cationic polyelectrolytes (see Fig. 16).

The U.S. Environmental Protection Agency³² found that *G. muris* cyst removal with a dual-media filter, operated with in-line flocculation chambers, demonstrated the four classic flocculation zones when alum was used as the coagulant, as shown in Table 1. The four zones are poor, good, poor, and very good flocculation, as the alum dose is increased. The results of this work cannot be translated to the ROWPU because in-line flocculation with alum is not used.

Determination of Optimal Coagulant Dose

The three methods commonly used to determine a priori the optimal dose of a coagulant are jar tests, zeta potential, and particle-size-distribution analyses. There is some disagreement among the various authorities as to how appropriate these methods are for determining the optimum dosage of a polymer with direct filtration.

According to Benefield et al.,¹¹ jar tests do not always give the optimum coagulant dosage for best filter performance in continuous-flow systems. On the other hand, the results of studies performed with various organic polymers and direct filtration, indicate that jar tests can be used for determining the optimum coagulant dosage for a given coagulant, but they cannot be used to select the best type of polymer.^{35,36,37} Yeh and Ghosh⁵ favor the particle-size-distribution approach for cationic polyelectrolytes.

O'Melia and Stumm⁷ have stated emphatically that zeta-potential measurements cannot be relied upon to determine the optimum coagulant dosage. Letterman et al.,³⁸ on the other hand, found that zeta-potential measurements can be used to obtain optimum filter performance with Cat-Floc T. Yeh and Ghosh⁵ found that the results of jar tests and zeta-potential measurements match closely in batch-coagulation tests. Ghosh et al.⁹ found that the results of zeta-potential measurements and particle-size-distribution analyses also match closely in batch tests. All of the above studies were performed with bentonite and/or kaolinite clays, or latex beads added to clean water.

None of these approaches is very useful for field operations because dilutions have to be prepared. The zeta potential measurement offers the best chance because one does not have to wait for the water to coagulate and the zeta potential of the particles entering the multimedia filter of the ROWPU can be determined quickly. Unfortunately, the usual zeta-

potential instrument is a delicate and expensive device not suited for use outside the laboratory. It is not known whether a simple, rugged zeta-potential meter could be developed by the instrumentation manufacturers.

The bull's-eye tube presently used to measure turbidity in the ROWPU cartridge-filter effluent represents one type of coagulant-dose control. Some problems with this approach include the lag time between changing the coagulant dose and filter response, the relatively poor performance that can be expected with all deep-bed filters immediately after backwashing, and the unloading of stored solids from the multimedia filter bed in the case of a sudden start-up after shutdown. All of these factors tend to confuse the ROWPU operator. Moreover, the bull's-eye method may not work with very clear raw waters.

One might suppose that nonturbid feed waters will cause no problems with the ROWPU. It was observed, however, that considerable portions of unreacted cationic polyelectrolyte tended to pass through a dual-media filter under such conditions.⁴² The passage of unreacted cationic organic polymers into the RO elements could foul the RO membranes quickly. If the RO section of the ROWPU should be bypassed under such conditions, then the unreacted polyelectrolyte will be contained in the drinking water. This would probably pose no health problem, but it is known that the chlorination of synthetic polymers can produce chlorinated organic compounds.

Initial Mixing

Recent investigation of direct filtration did not evaluate the best means of mixing the coagulant with the water, despite the findings of Vrale and Jorden,¹² which demonstrated that alum-coagulation efficiency is very much a function of how the alum is mixed with the water (see Fig. 6). Static mechanical mixers were used in most of the studies. The use of these mixers is exactly contrary to the recommendations of Vrale and Jorden, as well as the 1980 recommendations of the AWWA.⁴⁰ Pipe mixing was used in some of the studies, but the mean velocity gradients, G , were not estimated. Recommendations for G were made for cationic polyelectrolytes mixed with the water in mechanically stirred flash mixers. Ghosh *et al.*⁹ recommended a G of about 800 s^{-1} for the Cat-Floc group, and Stump and Novak³⁷ suggested a G ranging from 200 to 950 s^{-1} for various cationic polyelectrolytes. McCormick and King⁴⁵ utilized a G of 1650 s^{-1} for Cat-Floc T1 in their investigations.

Disinfection

If the reverse osmosis (RO) components of the ROWPU are bypassed, then the dosage of chlorine used for disinfection should be in accordance with the maximum dosage recommended in the field for disinfecting untreated (raw) water in water-sterilizing bags (commonly referred to as Lyster bags) and in canteens under worst-case conditions. For example, military personnel currently are instructed to add sufficient chlorine to the raw water in Lyster bags so that the total-available residual chlorine (i.e., the sum of free-available chlorine and combined-available chlorine), after 30 min of contact time, will be at least 5 mg/L;^{79,80} however, certain raw-water conditions such as the presence of especially resistant disease organisms, a pH of 8 or above, particularly cold water, or water containing large amounts of organic material may require more than normal chlorination for disinfection. The surgeon of a major command will designate when higher chlorine residuals, and consequently higher than normal chlorine dosages, are necessary to achieve disinfection. The command surgeon also should recommend maximum chlorination for the product water obtained from a ROWPU that is operated in the bypass mode.

For individual canteens (1 qt or 960 mL⁸⁰), military personnel ordinarily add iodine purification tablets as the disinfecting agent.^{79,80} Each tablet is designed to release 8 mg/L of iodine, and the minimum contact time required for disinfection is 25 min; two tablets are recommended to ensure adequate disinfection for turbid or colored water.^{79,80} When chlorine is not available as a disinfectant for water produced by ROWPU's operating in the bypass mode, the command surgeon should recommend the maximum dosage of iodine for the canteens being filled with such water.

Boiling water may be the only effective mechanism for disinfecting sources of drinking water in the event that neither chlorine or iodine is available. Nevertheless, raising the temperature of water to its boiling point and then boiling it for 15 to 20 min is practical on a small scale and in emergency situations.

ANALYTICAL METHODS

It has been proposed that the TDS conductivity meter of the Water Quality Monitor (WQM) be calibrated with solutions of sodium chloride. This is an appropriate procedure for the monitoring of TDS in the 600-gph ROWPU product water because the TDS in the product water should be essentially all NaCl if the ROWPU is used to treat ocean or estuarine water, and because the concentration of TDS in the product derived from non-

sea-salt waters should commonly be much less than any water-quality standard. This type of calibration will give incorrect results if used to measure the TDS concentration of most natural waters because they are not composed entirely of sodium and chloride ions. Therefore, this analytical method should not be used to evaluate the performance (TDS rejection) of the RO components of the ROWPU.

As far as can be judged by these reviewers, the free chlorine sensor included in the WQM should perform well with the clean product waters derived from the ROWPU if the chlorine sensor is calibrated in the field. It may be that the sensor will have to be recalibrated more frequently than the six-month period indicated by the manufacturer of the WQM.⁸⁹ The U.S. Army should check carefully to ascertain if the readings obtained with the WQM are accurate under a wide range of pH and temperature, and if a warm-up period of 10 min for the free-chlorine probe is adequate.

SUGGESTED IMPROVEMENTS

It is recognized that the U.S. Army would like to eliminate the MWPU. Even so, the performance of the ERDLATOR could be improved substantially by replumbing the chemical-feed lines in such a manner as to introduce the chemicals into the pipeline leading to the ERDLATOR. The stability of the sludge blanket then will be increased significantly.

The current 600-gph ROWPU represents a much greater problem. A study should be made to determine just how the polyelectrolyte should be mixed with the feed water to obtain optimal filter performance. The mean velocity gradient G can be altered by pipe inserts manufactured by several firms in the United States. The time required to obtain complete particle destabilization with each G should also be investigated, and the dimensionless number $G \cdot t$, where t is time, should also be derived.

It is not easy to judge the best method to obtain the optimal coagulant dose for the ROWPU as presently configured. All that can be encouraged here is the development and employment of a rugged and dependable zeta-potential meter.

REFERENCES

1. Small, M. J., J. B. Duncan, and P. H. Gibbs, The ROWPU Prefiltration System: Removal of Microorganisms, U. S. Army Medical Bioengineering Research and Development Laboratory, Fort Detrick, Frederick, MD, Technical Report 8104 (1982).
2. Ranadive, M. V. (for the Surgeon General), letter, DASG-PSP-E, Subject: Water Quality Standards (1984).
3. Weber, W. J., Jr., Physicochemical Processes for Water Quality Control, (Wiley-Interscience, New York, NY, 1972).
4. Tien, C., and A. C. Payatakes, "Advances in Deep Bed Filtration," AIChE J. **25**, 737-759 (1979).
5. Yeh, H., and M. M. Ghosh, "Selecting Polymers for Direct Filtration," J. Am. Water Works Assoc. **73**(4), 211-218 (1981).
6. Culp, R. L., "Direct Filtration," Am. Water Works Assoc. - California Section Water Treatment Forum V Direct Filtration Seminar (Oakland, CA, 1976).
7. O'Melia, C. R. and W. Stumm, "Theory of Water Filtration," J. Am. Water Works Assoc. **59**, 1393-1412 (1967).
8. Yao, K., M. T. Habibian, and C. R. O'Melia, "Water and Waste Water Filtration: Concepts and Applications", Environ. Sci. Technol. **5**, 1105-1112 (1971).
9. Ghosh, M. M., C. D. Cox, and T. M. Prakash, "Polyelectrolyte Selection for Water Treatment," J. Am. Water Works Assoc. **77**, 67-73 (1985).
10. Viessman, W., Jr., and M. J. Hammer, Water Supply and Pollution Control, 4th/Ed. (Harper and Row Publishers, Inc., New York, NY, 1985), 4th ed.
11. Benefield, L. D., J. F. Judkins, and B. L. Weand, Process Chemistry for Water and Wastewater Treatment (Prentice Hall, Inc., Englewood Cliffs, NJ, 1982).

12. Vrale, L., and R. M. Jorden, "Rapid Mixing in Water Treatment," I. Am. Water Works Assoc. 63, 52-58 (1971).
13. Cole, J. C., J. A. Farris, and N. Nickolaus, "Cartridge Filters," in Filtration Principles and Practices Part II, C. Orr, ed., Chemical Processing and Engineering, Vol. 10 (Marcel Dekker, Inc., New York, NY, 1979), pp. 202-259.
14. Warring, R. H., Filters and Filtration Handbook (Gulf Publishing Company, Houston, TX, 1981), pp. 16-17, 24-25, 88-98, 112-114.
15. Cheremisinoff, N. P., and D. S. Azbel, Liquid Filtration (Ann Arbor Science, Woburn, MA, 1983), pp. 103-107, 151.
16. Baumann, E. R., H. N. Armbrust, G. R. Bell, J. T. Fawls, J. V. Feuss, P. D. Haney, G. W. Moore, J. M. Sanchis, R. P. Schmitt, and T. L. Vander Velde, "Diatomite Filters for Municipal Use -- Task Group Report," I. Am. Water Works Assoc. 57, 157-180 (1965).
17. Carnahan, R. P., A. R. Anzzolin, and R. G. Ross, "Treatment of Brackish, Sea and Chemically Contaminated Fresh Water by Reverse Osmosis," Proc. National Conf. Environ. Engineering (ASCE, San Francisco, CA, 1979), pp. 729-743.
18. Headquarters, Department of the Army, Operator's Manual: Water Purification Unit, Reverse Osmosis, 600 GPH Trailer Mounted, Flatbed Cargo, 5 Ton-4 Wheel Tandem, Model ROWPU 600-1 (4610-01-093-2380), Department of the Army, Washington, DC, Technical Manual No. TM 5-4610-215-10 (1982).
19. Ciccone, V. J., V. J. Ciccone and Associates, Inc., personal communication with G. Chesler (1985).
20. Filterite Corp., Brunswick Technetics Filterite Bulletin No. 1603, Timonium, MD.
21. Ciccone, V. J., V. J. Ciccone and Associates, Inc., personal communication with B. Marinas and Z. Ungun (October 1983).

22. Lindsten, D. C., and R. P. Schmitt, "U. S. Army Field Practices in Coagulation", Water Works and Wastes Engineering 2(9), 94-96 (1965).
23. Ruiz, A., and R. P. Schmitt, Development and Evaluation of the Mobile Water Purification Unit, Project 8-75-05-012, Department of the Army, Engineer Research and Development Laboratories, Fort Belvoir, VA, Interim Report 1343 (1954).
24. Headquarters, Department of the Army, Operator's and Organizational Maintenance Manual, Water Purification Unit, Van-Type Body Mounted, Electric Driven, AC, 115, 208 V, Single- and 3-Phase, 60 Hertz, 1/20 to 2 HP; 3000 GPH (Met-Pro Model 3000V), Department of the Army, Washington, DC, TM 5-4610-223-12 (1980).
25. Headquarters, Department of the Army, Operator's and Organizational Maintenance Manual Water Purification Unit, Van Type Body Mounted, Electric Motor Driven, AC, DC, 115, 208V, Single- and 3-Phase, 60 Hertz, 1/20 to 2 HP; 1500 GPH; Model EMC-1500S, Department of the Army, Washington, DC, TM 5-4610-218-12 (1980).
26. Lowe, H. N., Jr., R. P. Schmitt, and C. H. Spaulding, "Army's New Mobile Water Purification Unit", Engineer. News-Rec. 151(13), 39-41 (1953).
27. Spaulding, C. H., H. N. Lowe, Jr., and R. P. Schmitt, "Improved Coagulation by the Use of Pulverized Limestone," I. Am. Water Works Assoc. 43, 793-802 (1951).
28. Donahew, A. L., Removal of Nerve Gas GB from Water under Cold-Weather Conditions 'Salty Dog VI', Project 8-75-07-214, Department of the Army, Engineer Research and Development Laboratories, Fort Belvoir, VA, Report 1434 (1955).
29. Conley, W. R. Jr., "Integration of the Clarification Process," I. Am. Water Works Assoc. 57, 1334-1340 (1965).
30. Moffet, W., "Comments on Integration of the Clarification Process," I. Am. Water Works Assoc. 58, 91-93 (1966).
31. Robeck, G. G., "Comments on Integration of the Clarification Process," I. Am. Water Works Assoc. 58, 94-96 (1966).

32. Logsdon, G. S., and K. Fox, "Getting Your Money's Worth from Filtration," I. Am. Water Works Assoc. 74, 249-256 (1982).
33. Logsdon, G. S., J. M. Symons, R. L. Hoye, Jr., and M. M. Arozarena, "Alternative Filtration Methods for Removal of Giardia Cysts and Cyst Models," I. Am. Water Works Assoc. 73, 111-118 (1981).
34. Harris, W. L., "High-Rate Filter Efficiency," I. Am. Water Works Assoc. 62, 517-522 (1970).
35. Adin, A., and M. Rebhun, "High Rate Contact Flocculation-Filtration with Cationic Polyelectrolytes," I. Am. Water Works Assoc. 66, 109-117 (1974).
36. Habibian, M. T., and C. R. O'Melia, "Particles, Polymers, and Performance in Filtration," J. Environ. Eng. Div., ASCE 101 (EE4), 567-583 (1975).
37. Stump, V. L. and J. T. Novak, "Polyelectrolyte Selection for Direct Filtration," I. Am. Water Works Assoc. 71, 338-342 (1979).
38. Letterman, R. D., R. R. Sama, and E. J. DiDomenico, "Direct Filtration Using Polyelectrolyte Coagulants," I. Am. Water Works Assoc. 71, 332-338 (1979).
39. Robeck, G. G., N. A. Clarke, and K. A. Dostal, "Effectiveness of Water Treatment Processes in Virus Removal," I. Am. Water Works Assoc. 54, 1275-1290 (1962).
40. Direct Filtration Subcommittee of the Am. Water Works Assoc. Filtration Committee, "The Status of Direct Filtration," I. Am. Water Works Assoc. 72, 405-411 (1980).
41. Trussell, R. R., A. R. Trussell, J. S. Lang, and C. H. Tate, "Recent Developments in Filtration System Design," I. Am. Water Works Assoc. 72, 705-710 (1980).
42. Carns, K. E., and J. D. Parker, "Using Polymers with Direct Filtration," I. Am. Water Works Assoc. 77, 44-49 (1985).

43. Monsevizt, J. J., D. J. Rexing, R. G. Williams, and J. Heckler, "Some Practical Experience in Direct Filtration," I. Am. Water Works Assoc. **70**, 584-588 (1978).
44. Rebhun, M., Z. Fuhrer, and A. Adin, "Contact Flocculation-Filtration of Organics Colloids," Water Filtration. Proc. Intern. Symposium "Water Filtration." R. Weiler and J. G. Janssens, Eds. (Antwerp, 1982).
45. McCormick, R. F., and P. H. King, "Factors that Affect Use of Direct Filtration in Treating Surface Waters," I. Am. Water Works Assoc. **74**, 234-242 (1982).
46. Hand, J., C. H. Tate, W. H. Moser, R. D. Rossmiller, and R. A. Perdue, "Direct Filtration versus Conventional Treatment: A Case Study," Proc. Am. Water Works Assoc. 1983 Annual Conference (Las Vegas, NV, 1983), pp. 1155-1168.
47. Cleasby, J. L., D. J. Hilmoie, and C. J. Dimitracopoulos, "Slow Sand and Direct In-line Filtration of a Surface Water," I. Am. Water Works Assoc. **76**, 44-55 (1984).
48. Duncan, J. B., Efficacy of Prechlorination on Biological Removal through the Multimedia Filter, U.S. Army Medical and Biological Research and Development Laboratory, Ft. Detrick, MD, draft letter report (undated - after February 1982).
49. Long, W. R., "Evaluation of Cartridge Filters for the Removal of Giardia lamblia Cyst Models from Drinking Water Systems," I. Environ. Health **45**, 220-225 (1983).
50. Radoski, E., Removal of Hydrocarbon Taste and Odor from Potable Water by Replaceable Carbon Containing Filter Cartridges, U. S. Army Mobility Equipment Research and Development Command, Fort Belvoir, VA, Technical Report No. 2334 (1981).
51. Cummins, A. B., "Clarifying Efficiency of Diatomaceous Filter Aids," Ind. Eng. Chem. **34**, 403-411 (1942).
52. Oulman, C. S., D. E. Burns, and E. R. Baumann, "Effect on Filtration of Polyelectrolyte Coatings of Diatomite Filter Media," I. Am. Water Works Assoc. **56**, 1233-1237 (1964).

53. Sanchis, J. M., and J. C. Merrell, Jr., "Studies on Diatomaceous Earth Filtration," I. Am. Water Works Assoc. 43, 475-495 (1951).
54. Syrotynski, S., "Experiences with Diatomite Filtration in New York State," I. Am. Water Works Assoc. 59, 867-877 (1967).
55. Syrotynski, S. and D. Stone, "Microscreening and Diatomite Filtration," I. Am. Water Works Assoc. 67, 545-548 (1975).
56. Hunter, J. V., G. R. Bell, and C. N. Henderson, "Coliform Organism Removals by Diatomite Filtration," I. Am. Water Works Assoc. 58, 1160-1169 (1966).
57. Burns, D. E., E. R. Baumann, and C. S. Oulman, "Particulate Removal on Coated Filter Media" I. Am. Water Works Assoc. 62, 121-126 (1970).
58. Brown, T. S., J. F. Malina, Jr., and B. D. Moore, "Virus Removal by Diatomaceous-Earth Filtration -- Part 1," I. Am. Water Works Assoc. 66, 98-102 (1974).
59. Brown, T. S., J. F. Malina, Jr., and B. D. Moore, "Virus Removal by Diatomaceous-Earth Filtration -- Part 2," I. Am. Water Works Assoc. 66, 735-738 (1974).
60. Amirhor, P., and R. S. Engelbrecht, "Virus Removal by Polyelectrolyte-Aided Filtration," I. Am. Water Works Assoc. 67, 187-192 (1975).
61. Lange, K. P., W. D. Bellamy, and D. W. Hendricks, Filtration of Giardia Cysts and Other Substances. Volume 1: Diatomaceous Earth Filtration, Environmental Protection Agency Project Summary, U.S. Environmental Protection Agency, Washington, DC, EPA-600/S2-84-114 (1984).
62. Kominek, E. G., "Industrial Applications of Diatomite Filters" Ind. Eng. Chem. 39, 1413-1419 (1947).
63. Shun Dar Lin, "Giardia lamblia and Water Supply," I. Am. Water Works Assoc. 77, 40-47 (1985).

64. War Department, Efficiency of Standard Army Purification Equipment and Diatomite Filters in Removing Cysts of Entamoeba histolytica from Water, Washington, DC, Report 834 (1944).
65. Jones, M. F., and F. S. Brady, "Removal of the cercariae of Schistosoma mansoni from water by filtration through diatomaceous silica in a small model filter," Public Health Reports 61, 1538-1543 (1946).
66. Baumann, E. R., and H. E. Babbitt, "The Removal of Entamoeba histolytica Cysts from Water by Porous Filter Septums either with or without Filter Aid," University of Illinois Engineering Experiment Station Bulletin 52(72), 1-39 (1955).
67. Logsdon, G. S., J. M. Symons, and R. L. Hoyer, "Water Filtration Techniques for Removal of Cysts and Cyst Models," in Waterborne Transmission of Giardiasis, U.S. Environmental Protection Agency, Washington, DC, EPA-600/9-79-001 (1979).
68. DeWalle, F. B., J. Engeset, and W. Lawrence, Removal of Giardia lamblia Cysts by Drinking Water Treatment Plants, Environmental Protection Agency Project Summary, U.S. Environmental Protection Agency, Washington, DC, EPA-600/S2-84-069 (1984).
69. Black, H. H., and C. H. Spaulding, "Diatomite Water Filtration Developed for Field Troops," I. Am. Water Works Assoc. 36, 1208-1221 (1944).
70. Pruett, P. B., and D. C. Lindsten, Use of Corps of Engineers Mobile Water Purification Unit and Auxiliary Processes for Destroying Bacterial Spores in Cold Water, Project 8-75-07-460, Department of the Army, Engineer Research and Development Laboratories, Fort Belvoir, VA, Report 1564-TR (1959).
71. Lindsten, D. C., and R. P. Schmitt, Expanded Perlite and Diatomaceous Earth for Army Field Water-Purification Units, Department of the Army, U. S. Army Mobility Equipment Research and Development Center, Fort Belvoir, VA, Report 1936 (1968).

72. Lindsten, D. C., W. J. Lacy, A. L. Donahew, P. B. Pruett, and F. L. Cobler, Removal of Radioactive Contaminants from Water with the Corps of Engineers Mobile Water Purification Unit 'Salty Dog IV', Project 8-75-07-214, Department of the Army, Engineer Research and Development Laboratories, Fort Belvoir, VA, Report 1406 (1955).
73. Laubusch, E.J., "Chlorination and Other Disinfection Processes," in Water Quality and Treatment: A Handbook of Public Water Supplies, prepared by The American Water Works Association, Inc. (McGraw-Hill Book Company, New York City, NY, 1971), Third ed., pp. 158-224.
74. National Research Council Safe Drinking Water Committee, Drinking Water and Health Disinfectants and Disinfectant By-Products Volume 7, National Academy Press, Washington, DC (1987).
75. Sobsey, M.D., "Inactivation of Health-Related Microorganisms in Water by Disinfection Processes," Water Sci. Technol. **21**(3), 179-196 (1989).
76. Akin, E.W., J.C. Hoff, and E.C. Lippy, Waterborne Outbreak Control: Which Disinfectant?," Environ. Health Perspect. **46**, 7-12 (1982).
77. Gershenfeld, L., "Chapter 11. Iodine, in "Disinfection, Sterilization, and Preservation 2nd Edition, S.S. Block, Ed. (Lea & Febiger, Philadelphia, PA, 1977), pp. 196-218.
78. National Research Council Safe Drinking Water Committee, Drinking ater and Health Volume 2, National Academy Press, Washington, DC (1980).
79. Headquarters, Department of the Army, Field Water Supply, Department of the Army, Washington, DC, TM 5-700 (1967), pp. 73-79, 113.
80. Headquarters, Department of the Army, Field Sanitation Team Training, Department of the Army, Washington, DC, TC 8-3 (1978), pp. 2-3 to 2-6.

81. Lippy, E.C., "Chlorination to Prevent and Control Waterborne Diseases," I. Am. Water Works Assoc. 78(1), 49-52 (1986).
82. Rose, J.B., "Occurrence and Significance of Cryptosporidium in Water," I. Am. Water Works Assoc. 80(2), 53-58 (1988).
83. Kenyon, K.F., Free Available Chlorine Disinfection Criteria for Fixed Army Installation Primary Drinking Water, U.S. Army Biomedical Research and Development Laboratory, Fort Detrick, Frederick, MD, Technical Report 8108/DTIC Nº. AD A114482 (1981).
84. Reckhow, D.A., and P.C. Singer, "Chlorination By-products in Drinking Waters: From Formation Potentials to Finished Water Concentrations," I. Am. Water Works Assoc. 82(4), 173-180 (1990).
85. Williams, D.E., S.D. Worley, S.B. Barnela, and L.J. Swango, "Bactericidal Activities of Selected Organic N-Halamines," Applied Environ. Microbiol. 53, 2082-2089 (1987).
86. Worley, S.D., and D.E. Williams, "Disinfecting Water with a Mixture of Free Chlorine and an Organic N-Halaminem," I. Am. Water Works Assoc. 80(1), 69-71 (1988).
87. Headquarters, Department of the Army, Operator's and Organizational Maintenance Manual. Water Quality Analysis/Sets. Preventive Medicine. Engineer, Department of the Army, Washington, DC, Technical Manual No. TM 5-6630-215-12 (1981).
88. Saugstad, E. S., "Water Quality Analyses in Army Field Operations", U.S. Army Environmental Hygiene Agency, Fort Meade, MD, memorandum to COL Herwig, Washington, DC (1980).
89. Foster-Miller, Inc., Operation and Service Instructions for the Water Quality Monitor, Foster-Miller, Inc., Waltham, MA, DRAFT (1984).

90. Lund, N. H., "Recommended Changes to the Water Quality Analysis Set-Preventive Medicine", U.S. Army Environmental Hygiene Agency, Aberdeen Proving Ground, MD, letter to Mr. Probst, U.S. Army Belvoir Research and Development Center, Fort Belvoir, VA (1984).
91. American Public Health Association, American Water Works Association, and Water Pollution Control Federation, Standard Methods for the Examination of Water and Wastewater (American Public Health Association, Washington, DC, 1985), 16th ed.
92. Rubin, L., G. Avarbock, W. Schroeder, J. Aplin, and J. Langer, Development of an Automated Water Quality Monitor, Foster-Miller, Inc., Waltham, MA, Report prepared for the U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, VA (1984).
93. Headquarters, Department of the Army, Sanitary Control and Surveillance of Water Supplies at Fixed and Field Installations, Department of the Army, Washington, DC, TB MED 229 (1989).
94. White, G. C., "A Discussion of the Chlorine Residual Monitoring System in the U.S. Army Field Water Supply Monitoring Facility," a report to Dr. Robert E. Selleck, Department of Civil Engineering, University of California at Berkeley, Berkeley, CA (1985).
95. Oliveri, A. W., R. C. Cooper, and R. E. Danielson, "Turbidity and Color," in Evaluation of Military Field-Water Quality: Volume 4. Health Criteria and Recommendations for Standards. Part 1. Chemicals and Properties of Military Concern Associated with Natural and Anthropogenic Sources, J. I. Daniels, Ed., Lawrence Livermore National Laboratory, Livermore, CA, UCRL-21008 Vol. 4, Part 1 (1988).
96. D'Antonio, R. G., R. E. Winn, J. P. Taylor, T. L. Gustafson, W. L. Current, M. M. Rhodes, G. W. Gary, Jr., and R. A. Zajac, "A Waterborne Outbreak of Cryptosporidiosis in Normal Hosts," Ann. Intern. Med. 103 (6, pt. 1), 886-888 (1985).

97. Current, W. L., "Cryptosporidium and Cryptosporidiosis," in Acquired Immune Deficiency Syndrome, M. S. Gottlieb and J. D. Groopman, Eds. (Alan R. Liss, Inc., New York, NY, 1984), pp. 355-373.
98. Sterling, C., University of Arizona, Tucson, AZ, personal communication,(1986).

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